Thrust 3: Electrical Characterization Overview/ Effect of Strain on Trap-related Reliability Mechanisms

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A. Koehler
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Outline

- Motivation and review from last meeting
- Piezoresistance measurements
- Simulation of strain effects on 2DEG resistivity
- Summary

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- **Motivation and review from last meeting**
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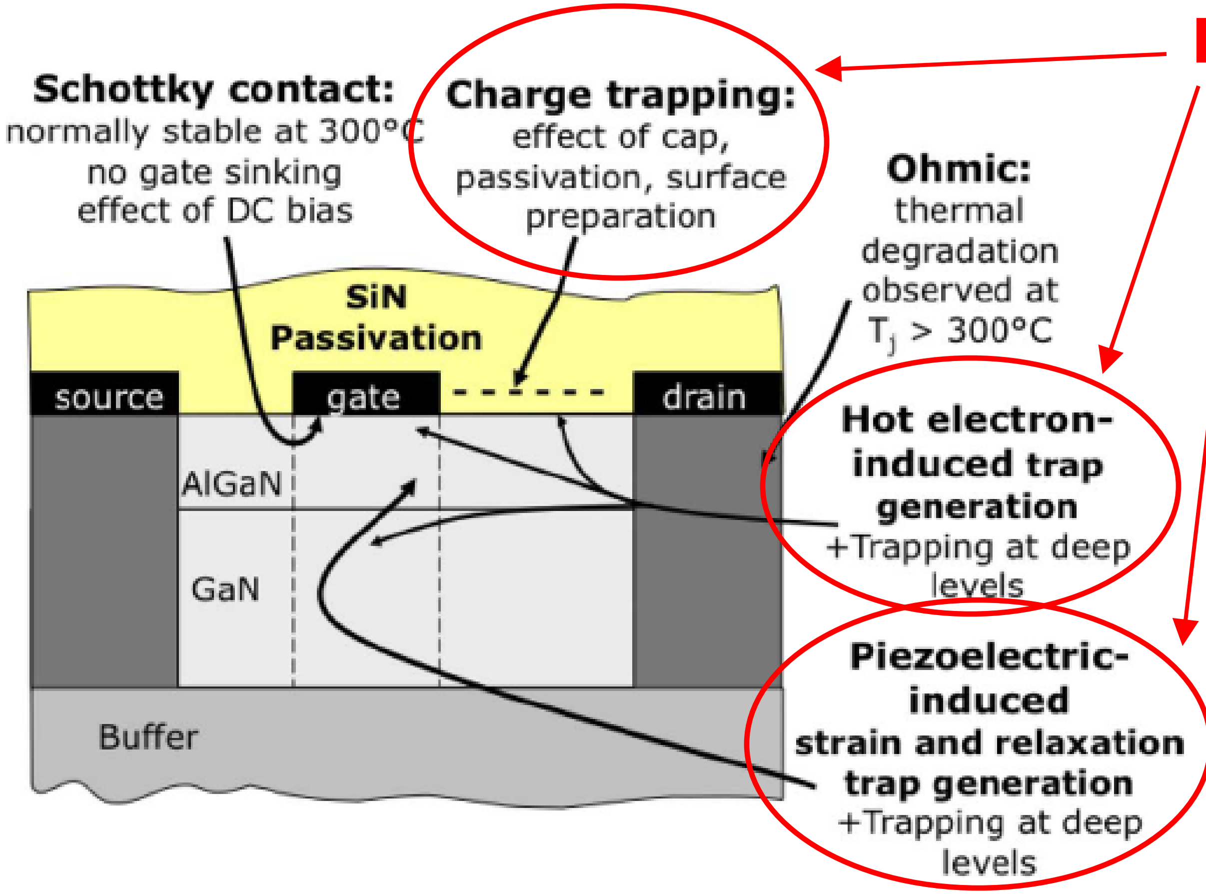
Failure Mechanisms in GaN HEMTs



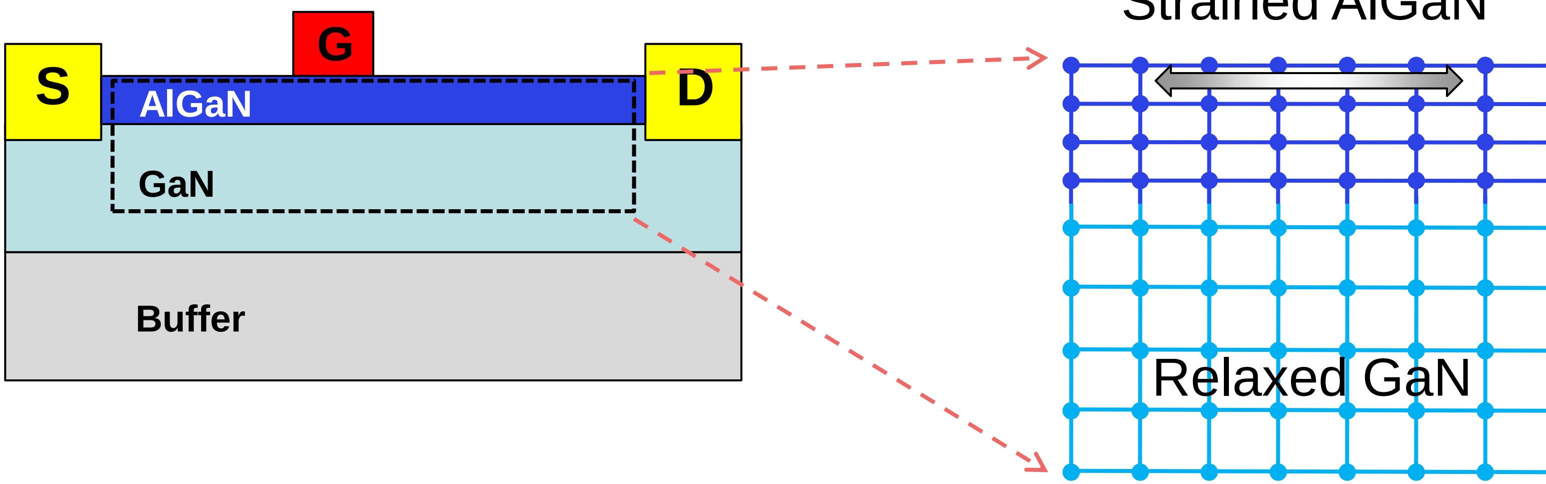
Influenced by stress

- carrier mobility
- polarization and 2DEG
- trap energy levels
- Schottky barrier height
- bandgap
- generation of traps

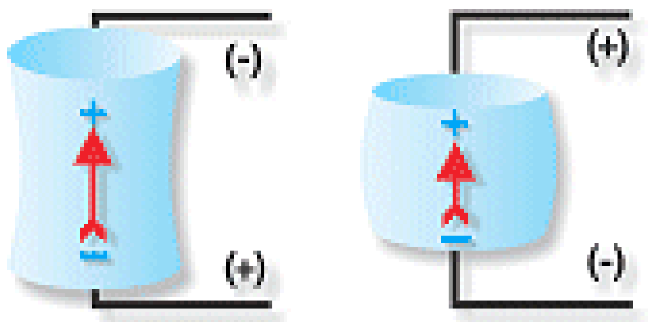
G. Meneghesso, et al., IEEE Trans on Device and Materials Reliability, Vol. 8, 2, 2008

Stress in GaN HEMT Devices

Lattice mismatch (built-in) stress:



Inverse piezoelectric (generated) stress:



$$\begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \\ \varepsilon_{xy} \end{pmatrix}$$

Outline

- Motivation and review from last meeting
- **Piezoresistance measurements**
- Simulation of strain effects on 2DEG resistivity
- Summary

Piezoresistance

- Piezoresistance: Change in electrical resistance with mechanical stress

Piezoresistance coefficient (π): $\pi = \frac{\Delta R/R}{\sigma}$ $\sigma = \text{Stress}$

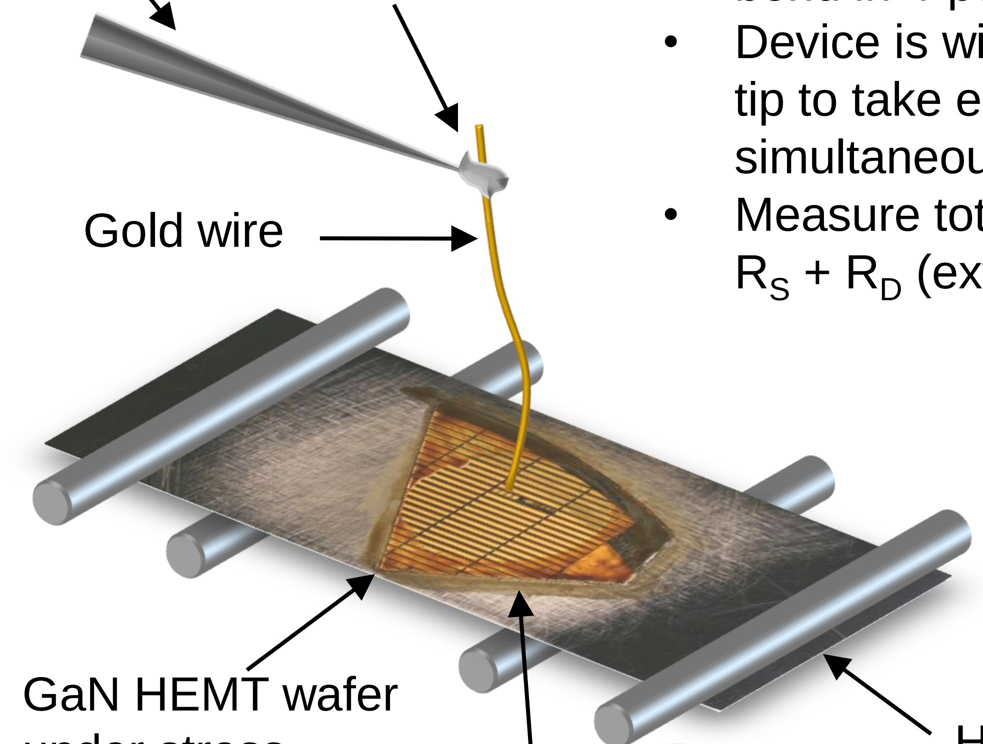
Gauge factor (GF): $GF = \frac{\Delta R/R}{\varepsilon}$ $\varepsilon = \text{Strain}$

- Stress alters semiconductor band structure impacting reliability and failure mechanisms of GaN HEMT devices

- Measure piezoresistance of GaN HEMT channel:
  - hot-carrier injection/trapping
  - impact ionization

- Experiment on two GaN HEMT samples from different manufacturers

Experimental Setup



- GaN HEMT wafer samples too small to directly bend in 4-point bending setup
- Device is wirebonded and connected to probe tip to take electrical measurements while simultaneously applying stress
- Measure total device resistance (R_{TOT}) = R_{CH} + R_S + R_D (extracted by 4-point measurement)

4-Point Wafer Bending Experiments

Strain Engineering to Improve Data Retention Time in Nonvolatile Memory

R. Arghavani, N. Derhacobian, V. Banthia, M. Balseanu, N. Ingle, H. M'Saad, S. Venkataraman, E. Yieh, Z. Yuan, L.-Q. Xia, Z. Krivokapic, U. Aghoram, K. MacWilliams, and S. E. Thompson

Impact of mechanical stress on gate tunneling currents of germanium and silicon *p*-type metal-oxide-semiconductor field-effect transistors and metal gate work function

Youn Sung Choi,[1] Toshinori Numata,[1,a)] Toshikazu Nishida,[1] Rusty Harris,[2] and Scott E. Thompson[1,b)]

Comparison of Uniaxial Wafer Bending and Contact-Etch-Stop-Liner Stress Induced Performance Enhancement on Double-Gate FinFETs

Sagar Suthram, *Student Member, IEEE*, M. M. Hussain, *Member, IEEE*, H. R. Harris, *Member, IEEE*, C. Smith, H.-H. Tseng, *Fellow, IEEE*, R. Jammy, *Member, IEEE*, and S. E. Thompson, *Fellow, IEEE*

Abstract—Longitudinal piezoresistance (π) coefficie[nts] and p-type double-gate (DG) FinFETs with sidewall along (110) surface and ⟨110⟩ channel direction are mea[sured] wafer-bending experiments (51.4 and -37×10^{-11} Pa and p-FinFETs, respectively) and are found to differ fro[m] (110) (31.2 and -71.8×10^{-11} Pa^{-1} for n- and p-Si, resp[ectively]). Compressive and tensile contact-etch-stop liners (CESLs) ricated on DG FinFETs and are found to induce highe[r] stress than in planar MOSFETs, with 30% enhanceme[nt] saturation current for the shortest channel-length devic[es] n- and p-MOSFETs, whereas the long devices show li[ttle] enhancement. The channel-length dependence of the enh[ancement] suggests that stress coupling into the FinFET channels CESL occurs via the fin extensions and not through the g[ate].

Index Terms—Contact-etch-stop liners (CESLs), piezoresistance, wafer bending and strain.

I. INTRODUCTION

Piezoresistance Coefficients of (100) Silicon nMOSFETs Measured at Low and High (∼1.5 GPa) Channel Stress

S. Suthram, J. C. Ziegert, T. Nishida, and S. E. Thompson, *Fellow, IEEE*

Strain-induced changes in the gate tunneling currents in *p*-channel metal–oxide–semiconductor field-effect transistors

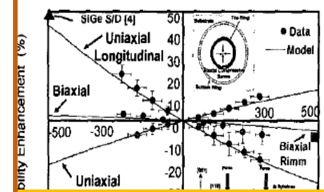
X. Yang, J. Lim, G. Sun, K. Wu, T. Nishida, and S. E. Thompson[a)]
Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida 32611

Key Differences For Process-induced Uniaxial vs. Substrate-induced Biaxial Stressed Si and Ge Channel MOSFETs

S.E. Thompson, G. Sun, K. Wu, J. Lim, and T. Nishida
University of Florida, PO Box 116130, Gainesville FL 3261

Abstract
For both n and pMOSFETs, this paper confirms via con-

with the uniaxial process stress data, enhanced hole mobility is observed at both low and high vertical fields as shown in [Fi]g. 2. Wafer bending uniaxial tensile stress also shows a [sm]all threshold voltage shift for nMOSFETs which will be [pr]esented in the next section.



Mechanical stress altered electron gate tunneling current and extraction of conduction band deformation potentials for germanium

Youn Sung Choi, Ji-Song Lim, Toshinori Numata,[a)] Toshikazu Nishida, and Scott E. Thompson[b)]
Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida 32611, USA

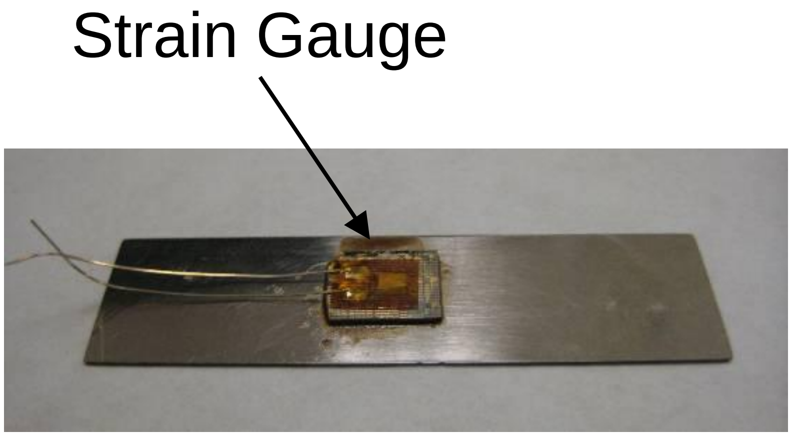
(Received 9 July 2007; accepted 14 September 2007; published online 30 November 2007)

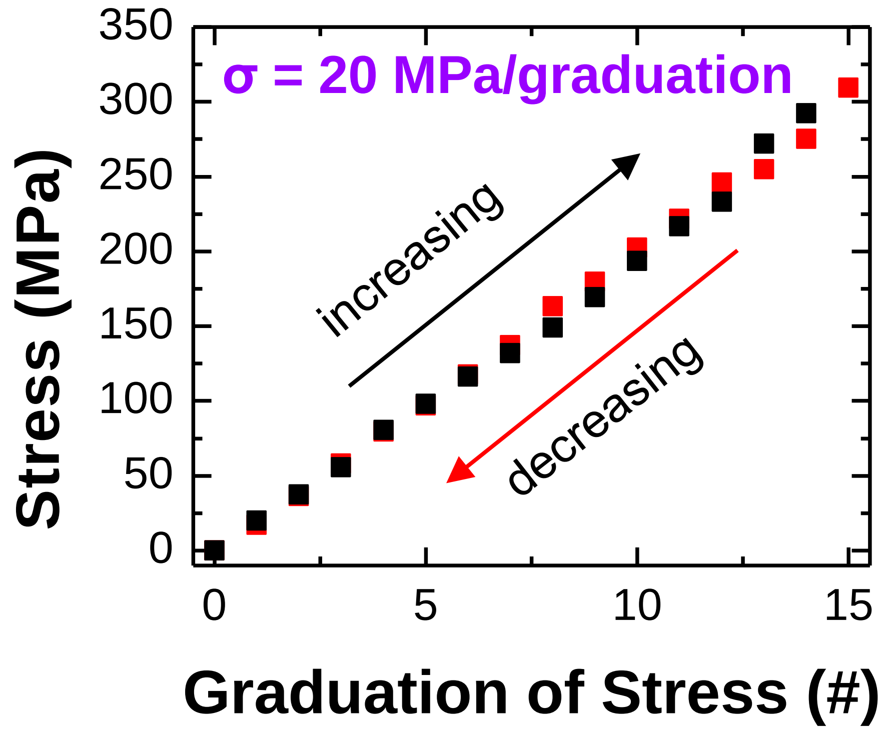
Strain altered electron gate tunneling current is measured for germanium (Ge) metal–oxide–semiconductor devices with HfO_2 gate dielectric. Uniaxial mechanical stress is applied using four-point wafer bending along [100] and [110] directions to extract both dilation and shear deformation potential constants of Ge. Least-squares fit to the experimental data results in Ξ_d and Ξ_u of −4.3±0.3 and 16.5±0.5 eV, respectively, which agree with theoretical calculations. The dominant mechanism for the strain altered electron gate tunneling current is a strain-induced change in the conduction band offset between Ge and HfO_2. Tensile stress reduces the offset and increases the gate tunneling current for Ge while the opposite occurs for Si. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2809374]

I. INTRODUCTION

the conduction band constant energy ellipsoids around th

Stress Calibration





- Strain gauge measures strain on top surface of GaN HEMT wafer
- Bending does not permanently deform metal plate
- Strain gauge calibrated:
  - optical curvature
  - force sensor measurements
  - 4-point bending equation

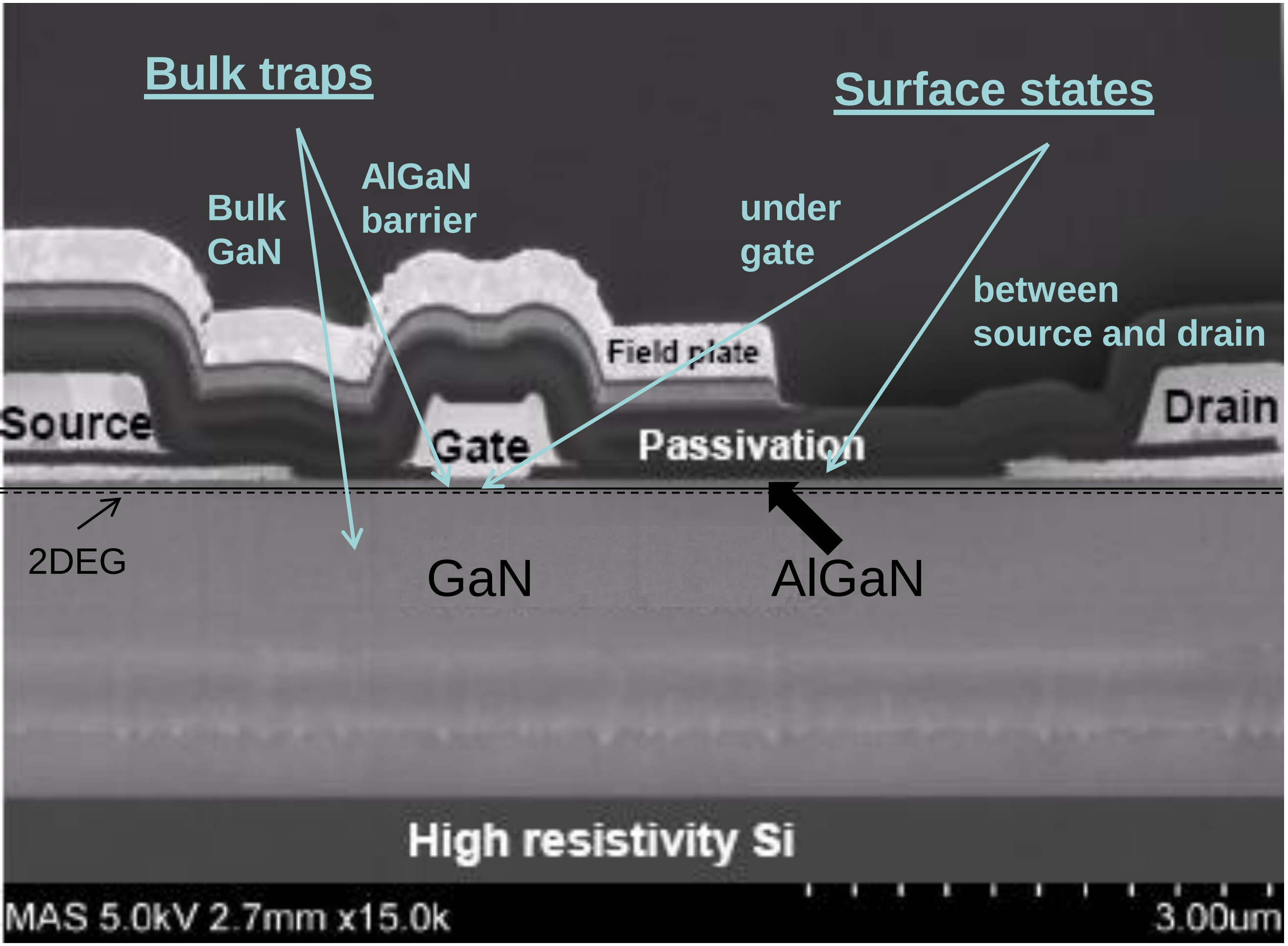
Wide Range of Published GaN HEMT GFs

Reference	GF	ΔR/R	ε (%)	σ (MPa)	Method of Stressing
[1]	-4	0.14%	.03	95	3-point bending
[2]	-42	0.2%	.005	15	3-point bending
[3]	-75	3.5%	.04	126	3-point bending
[4]	-90	15%	0.167	525	Cantilever
[5]	-350	5%	.0143	45	Lever-Mass
[6]	-1,259	1.7%	1.35×10^{-4}	0.42	Cantilever
[7]	-38,889	15%	3.85×10^{-4}	1.2	Circular Membrane

Largest change in resistance measured is ~15%
Could result from charge trapping effects?

[1] R. Gaska, et al, *APL*vol. 72, pp. 64-66, 1998.
[2] M. Eickhoff, et al, JAP, vol. 90, 3383-3386, 2001.
[3] C. T. Chang, et al, *IEEE Electron Device Letters,* vol. 30, pp. 213-2152009.
[4] T. Zimmermann, et al, *IEE Electron Device Letters,* vol. 27, pp. 309-312, 2006.
[5] O. Yilmazoglu, K. et al, *EICE Trans Electron,* vol. E89-C, pp. 1037-1041, 2006
[6] B. S. Kang, et al, *APL,* vol. 83, 4845-4847, 2003.
[7] B. S. Kang, et al, APL, vol. 85, pp. 2962-2964, 2004.

Charge Traps in GaN HEMTs



Cause

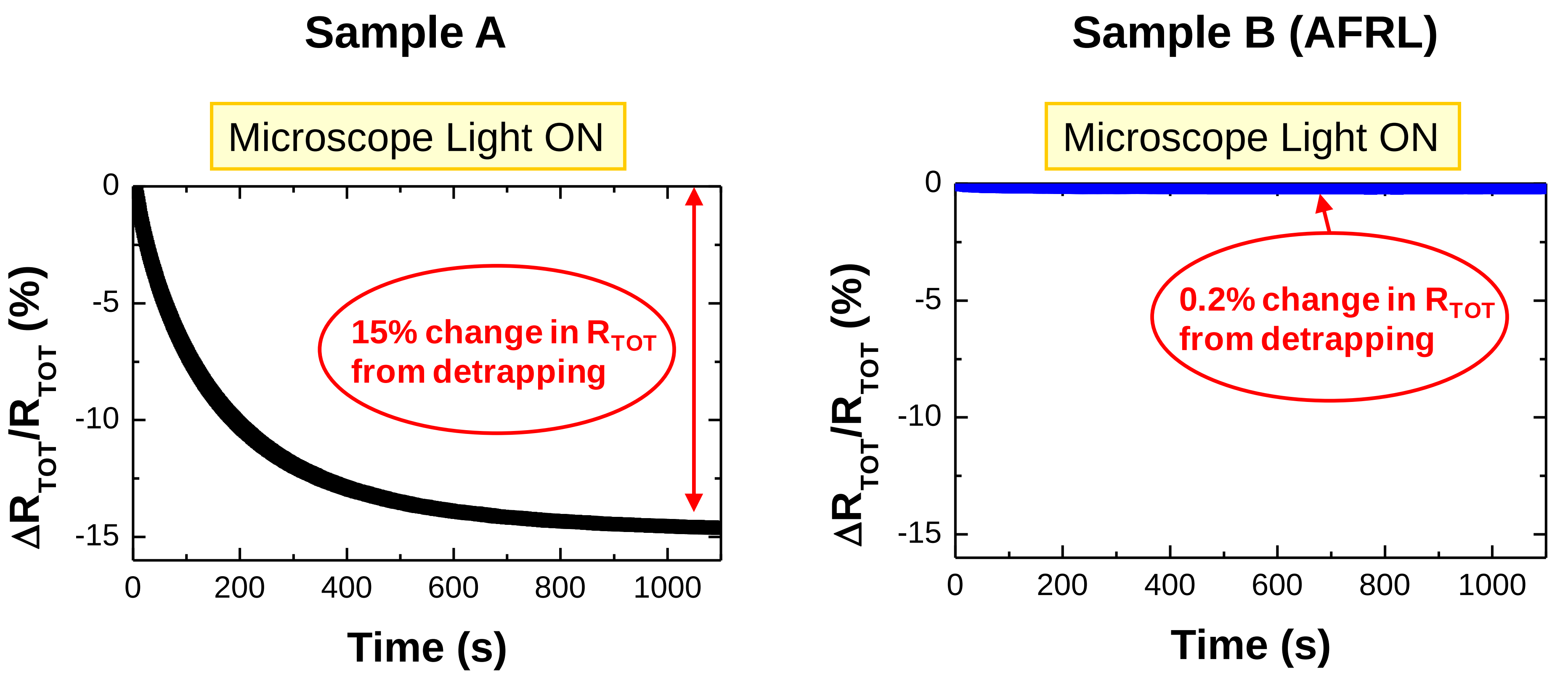
- growth-*as fabricated* traps
- post-growth process *as fabricated* traps
- hot-carrier injection *generated* traps
- inverse piezoelectric strain *generated* traps

Effect

- current collapse
- gate-lag
- drain-lag
- ΔV_T
- increased I_G
- light sensitivity
- breakdown

Significance of trapping effects depend on processing conditions

Effect of Light on Device Resistance

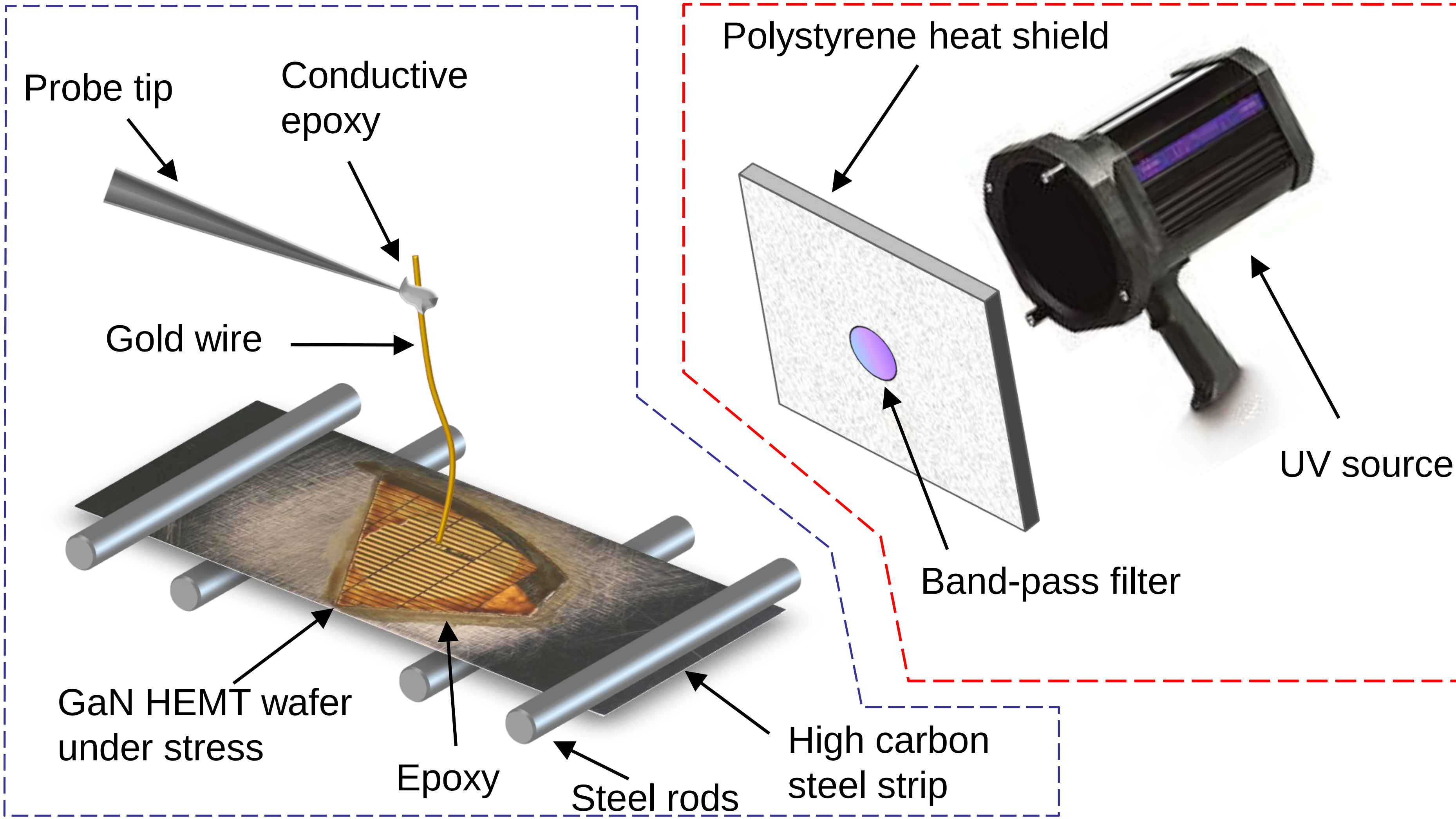


- Microscope light detraps trapped charge decreasing R_{TOT}
- Sample B (AFRL) is less sensitive to light (fewer traps)

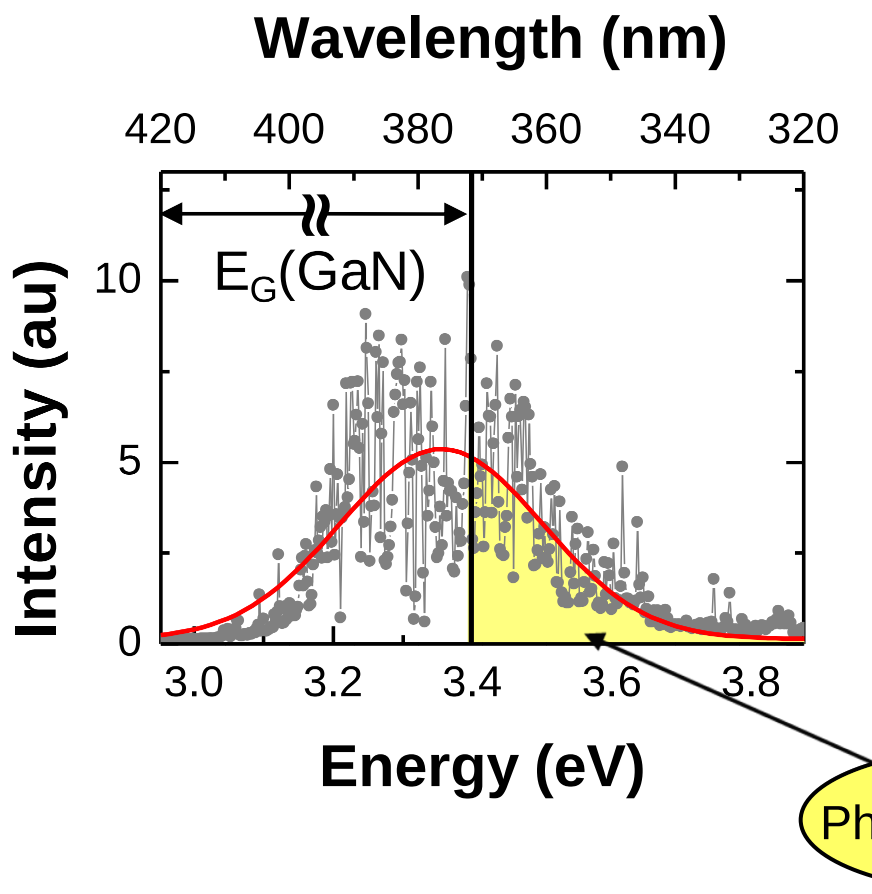
Experimental Setup – UV Illumination

Electrical measurements under stress

Elimination of charge trapping effects

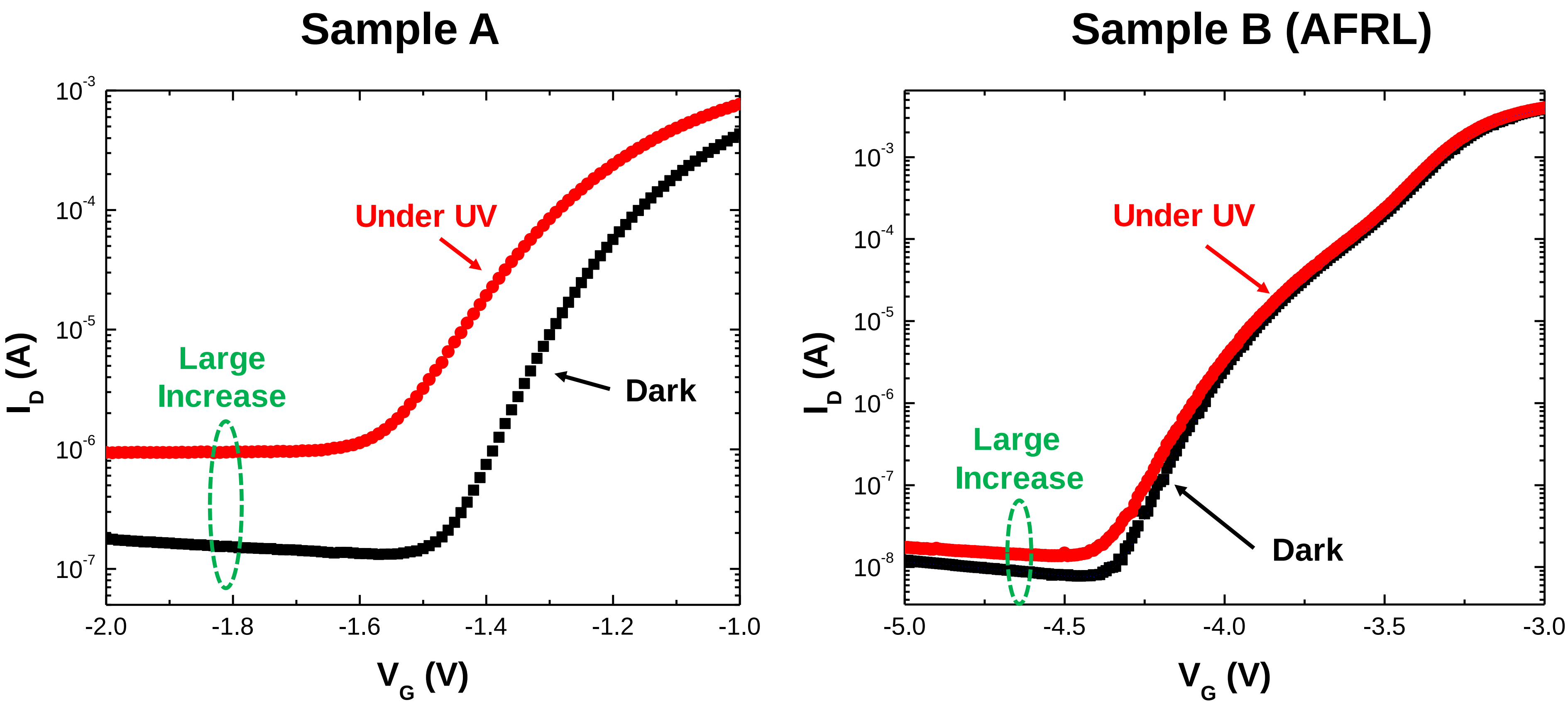


Output of UV Light Source



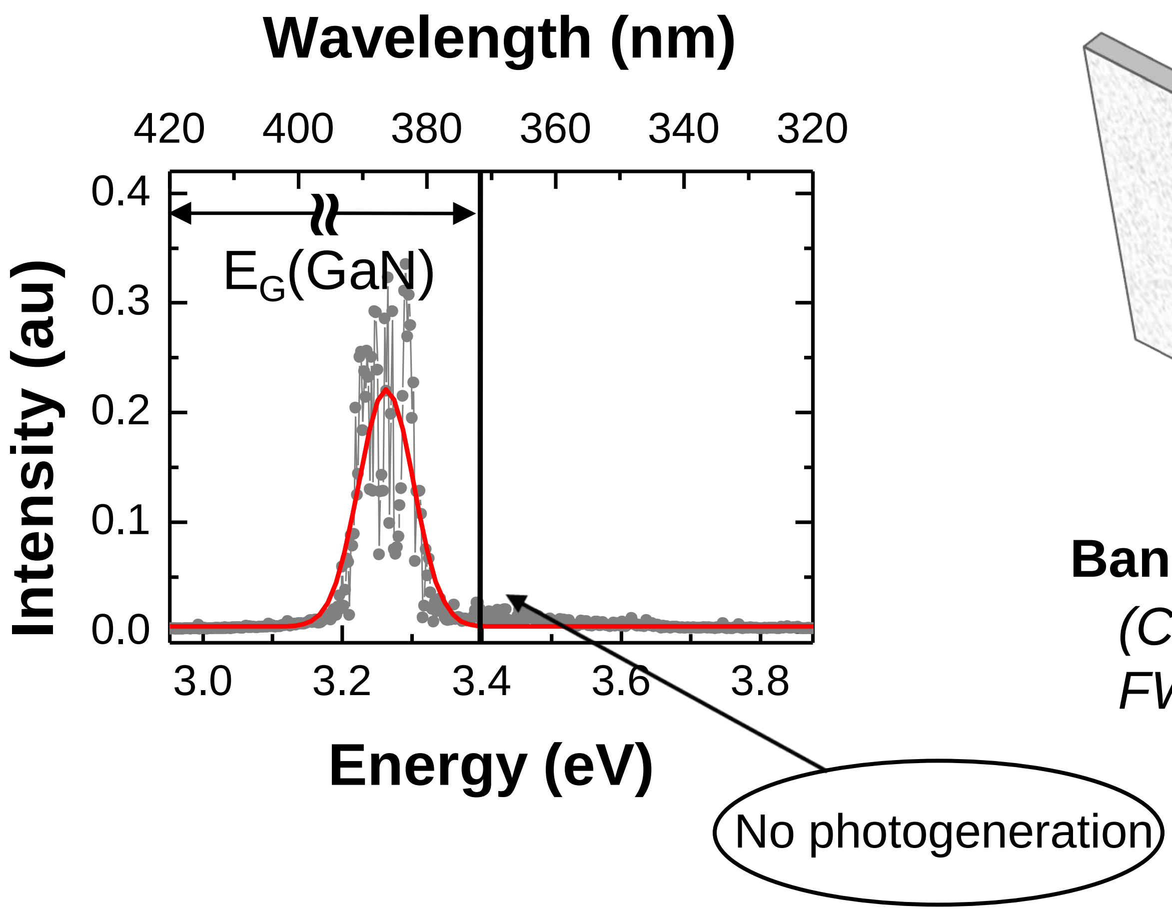
- Near bandgap photons will photoionize trapped charge
- Photons with energy > E_G(GaN) photogenerate e-h pairs

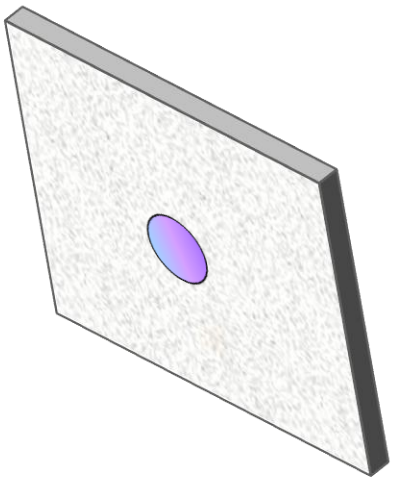
Effect of UV Light on I_D-V_G



- Photoionization of trapped charge shifts V_T
- Photogenerated e-h pairs increases offstate I_D
- AFRL sample is less sensitive to light (fewer traps)

Output of Filtered UV Light Source



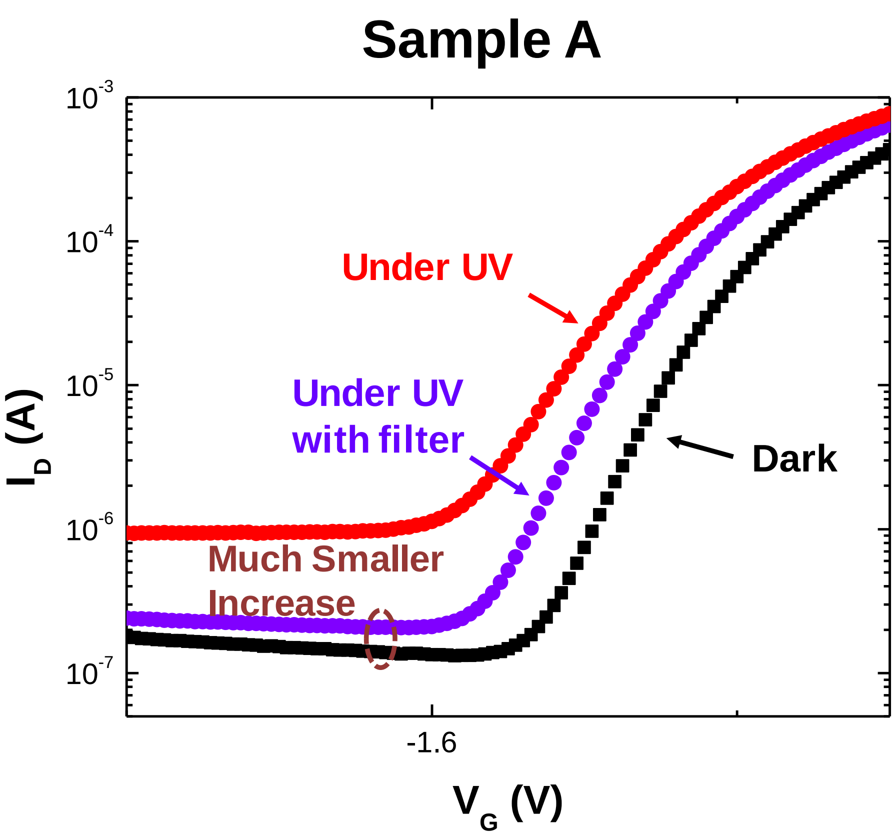


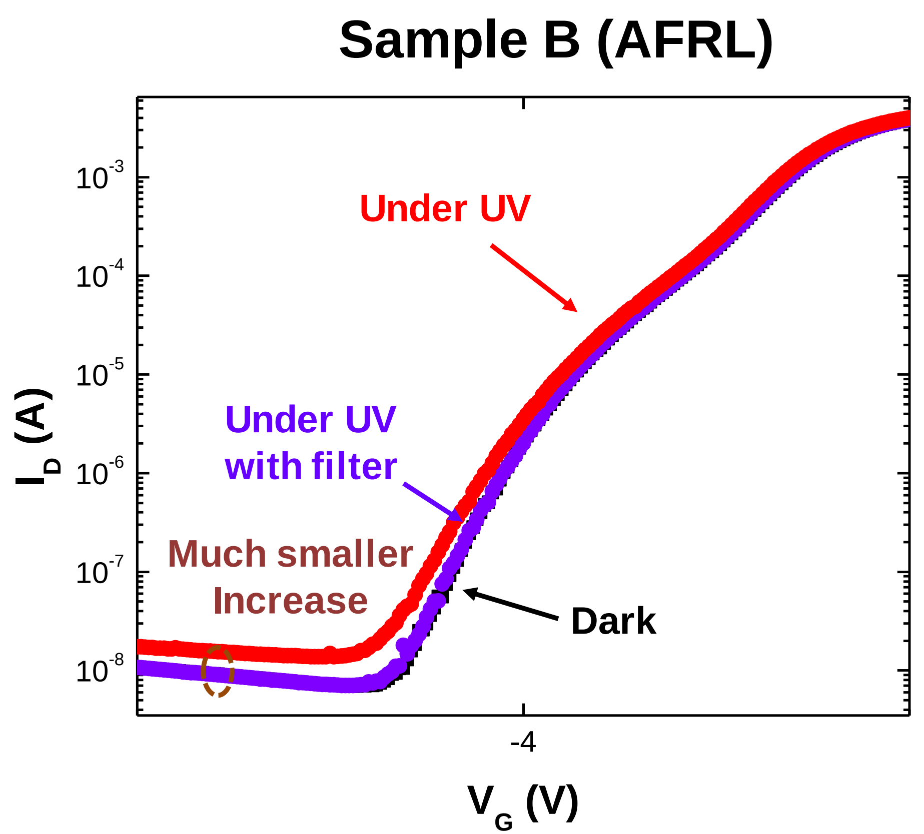
Band Pass Filter

(CWL=380nm, FWHM=10 nm)

- Near bandgap photons still photoionize trapped charge
- No photons with energy > E_G(GaN) to photogenerate e-h pairs

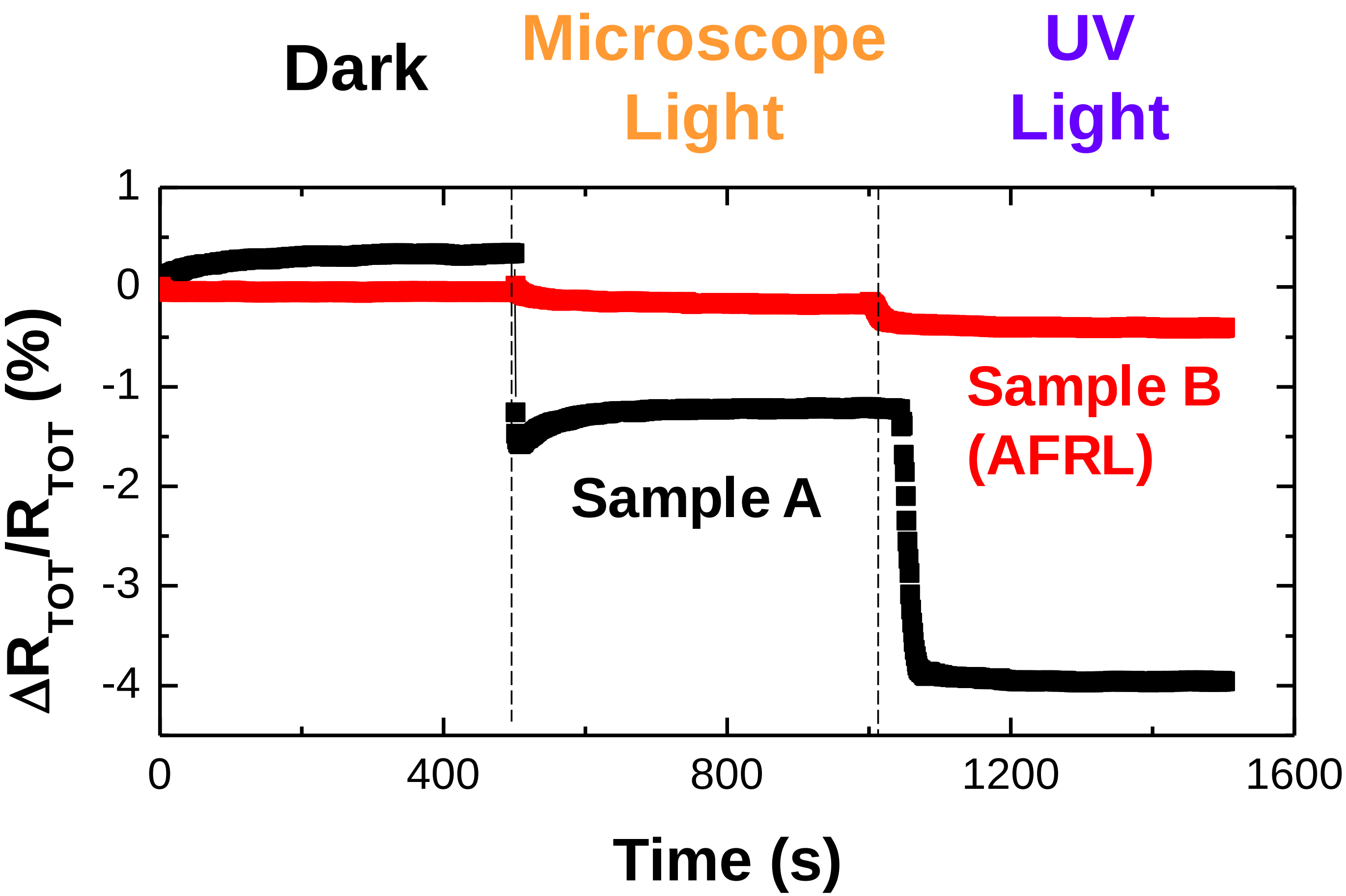
Effect of Filtered UV Light on I_D-V_G





- BP filter eliminates photons > E_G(GaN) and does not increase offstate I_D
- Only parallel shift in V_T is observed from charge detrapping
- AFRL sample has less sensitivity to light (fewer traps)

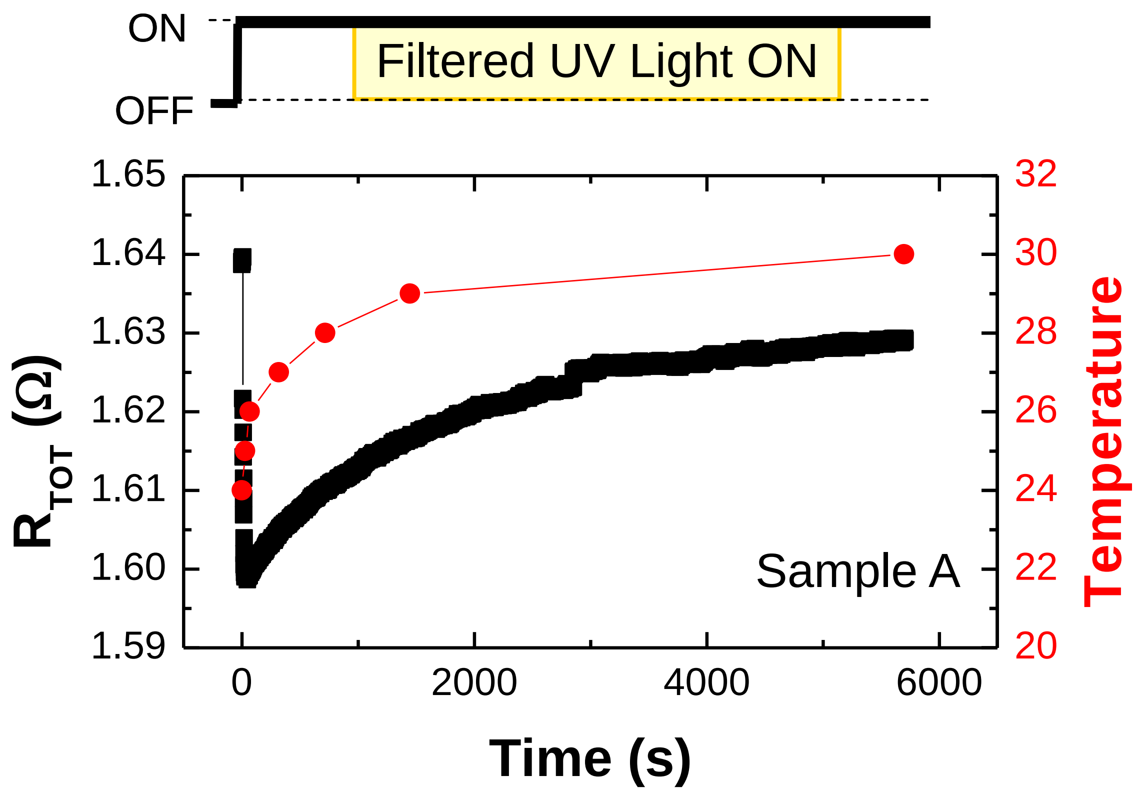
Light Sensitivity



- Sample B (AFRL) is less sensitive (fewer traps)
- Filtered UV used to stabilize R_{TOT} measurements to obtain piezoresistance

Infrared Heating From UV Source

No heat shield

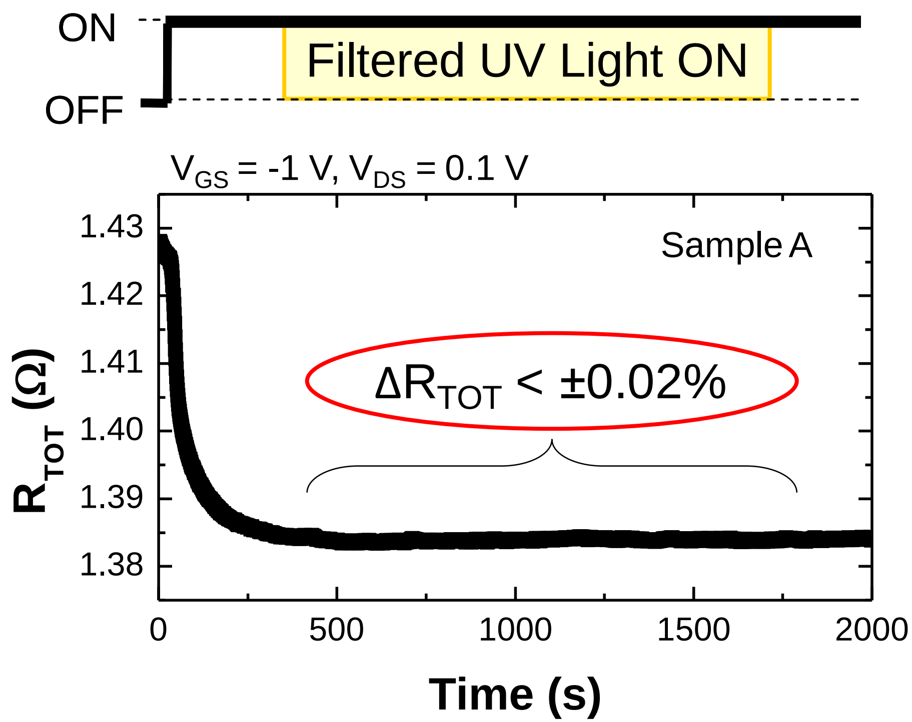


- Thermocouple placed near sample
- Infrared heating from source prevents stable resistance measurements

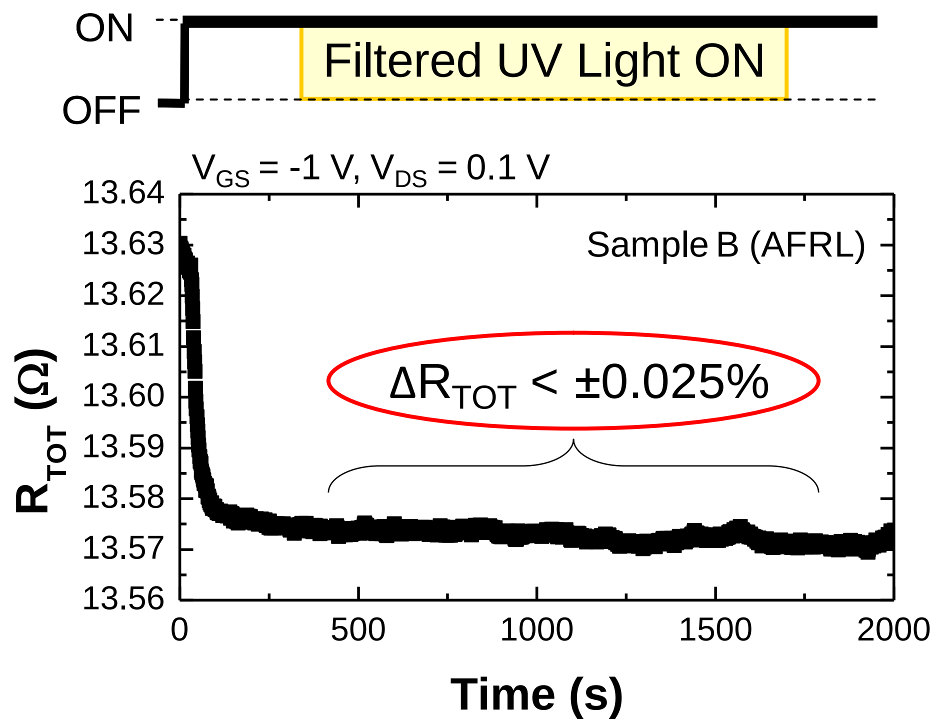
Device Resistance Stabilized

With heat shield

Sample A

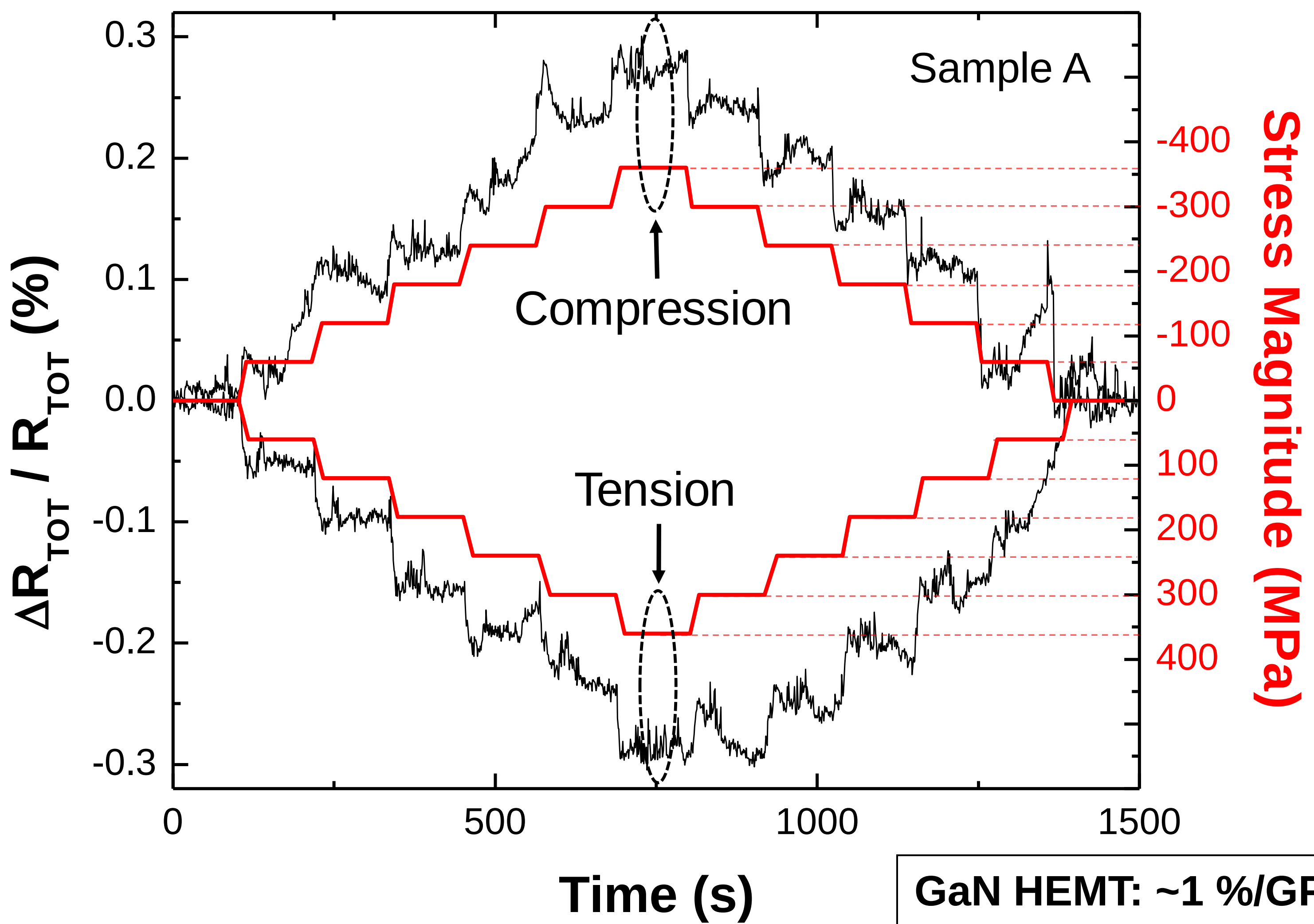


Sample B (AFRL)



- With polystyrene shield, < 0.025% stability in measured R_{TOT} is achieved
- Piezoresistance can be measured

Measured Piezoresistance



GaN HEMT: ~1 %/GPa
Si nMOS: ~31 %/GPa

GaN HEMT Piezoresistance

Wide range of published gauge factors (GF)

Reference	GF	ΔR/R	ε (%)	σ (MPa)	Method of Stressing
This work	**-2.6**	**0.3%**	**0.114**	**360**	**4-point bending**
[1]	-4	0.14%	.03	95	3-point bending
[2]	-42	0.2%	.005	15	3-point bending
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- **Simulation of strain effects on 2DEG resistivity**
- Summary
- Future plans and goals

Determination of Band Parameters

IEEE ELECTRON DEVICE LETTERS, VOL. 25, NO. 11, NOVEMBER 2004 731

Comparison of Threshold-Voltage Shifts for Uniaxial and Biaxial Tensile-Stressed n-MOSFETs

Abstract—
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APPLIED PHYSICS LETTERS **89**, 073509 (2006)

Measurement of conduction band deformation potential constants using gate direct tunneling current in *n*-type metal oxide semiconductor field effect transistors under mechanical stress

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JOURNAL OF APPLIED PHYSICS **102**, 104507 (2007)

Mechanical stress altered electron gate tunneling current and extraction of conduction band deformation potentials for germanium

Youn Sung Choi, Ji-Song Lim, Toshinori Numata,[a)] Toshikazu Nishida, and Scott E. Thompson[b)]
Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida 32611, USA

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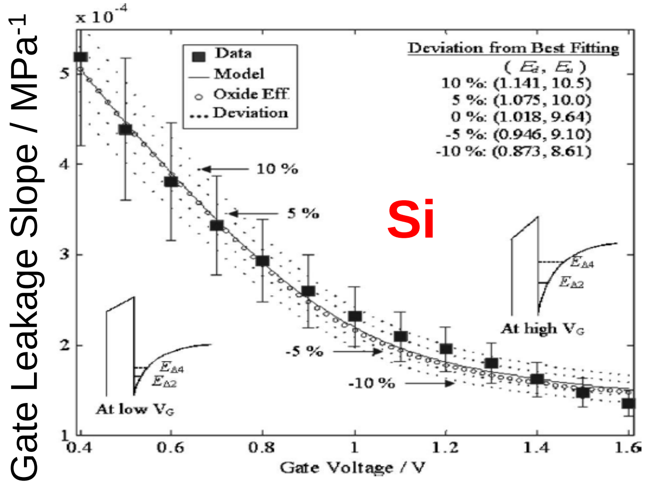
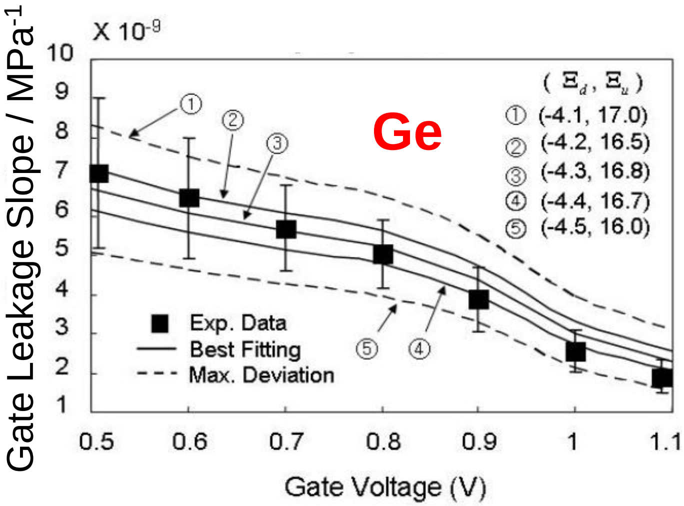
Strain altered electron gate tunneling current is measured for germanium (Ge) metal–oxide–semiconductor devices with HfO_2 gate dielectric. Uniaxial mechanical stress is applied using four-point wafer bending along [100] and [110] directions to extract both dilation and shear deformation potential constants of Ge. Least-squares fit to the experimental data results in Ξ_d and Ξ_u of −4.3±0.3 and 16.5±0.5 eV, respectively, which agree with theoretical calculations. The

Extraction of Deformation Potentials



[APL, vol. 89, pp. 073509, 2006]

(eV)	Si
Ξ_d	1.0±0.1[c], 1.1[b], 1.2[b], 1.13[b], 5[b],
Ξ_u	9.6±1.0[c], 10.5[b], 8.86[b], 9.2[b], 7.3[b], 9.29[b],
a	2.1[b], 2.46[b], 2.06[b],
b	-2.33[b], -1.5[b], -2.1[b], -2.2[b], -2.12[b], -2.35[b], -2.58[b], -2.27[b]
d	-4.75[b], -3.4[b], -4.85[b], -5.3[b], -3.69[b]

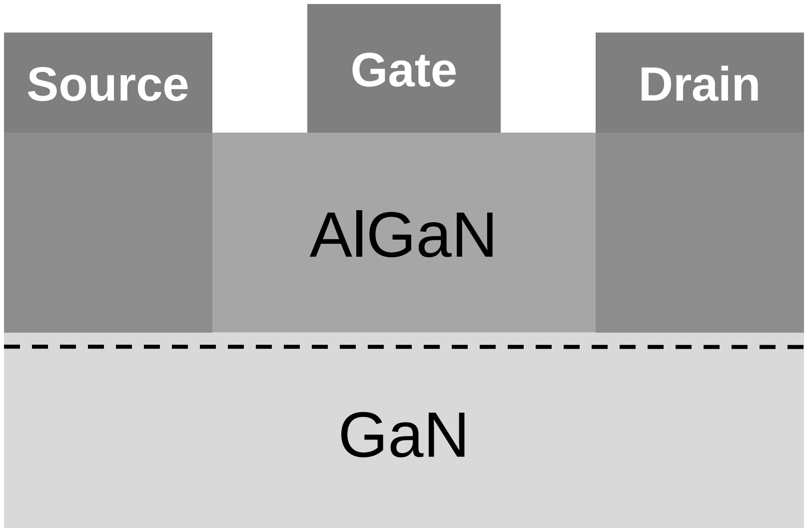


[JAP, vol. 102, pp. 104507, 2007]

(eV)	Ge
Ξ_d	-4.3±0.3[a], -4.43[b], -12.3~-10.5[b], -6.6[b],
Ξ_u	16.5±0.5[a], 16.8[b], 11.07[b], 15.13[b], 16.2[b], 15.9~19.3[b],
a	2.0[b], 1.24[b], 2.09[b], -12.7[b], 1.39[b]
b	-2.16[b], -2.1[b], -2.2[b], -2.08[b], -2.5[b], -2.55[b], 2.86[b], -3.11[b]
d	-6.06[b], -3.5[b], -4.4[b], -3.7[b], -4.5[b], -5.3[b], -4.65[b], -7.0[b]

[a] [JAP, vol. 102, pp. 104507, 2007]
[b] [JAP, vol. 80, pp. 2234, 1996]
[c] [APL, vol. 89, pp. 073509, 2006]

Factors that Need to be Considered



2DEG channel

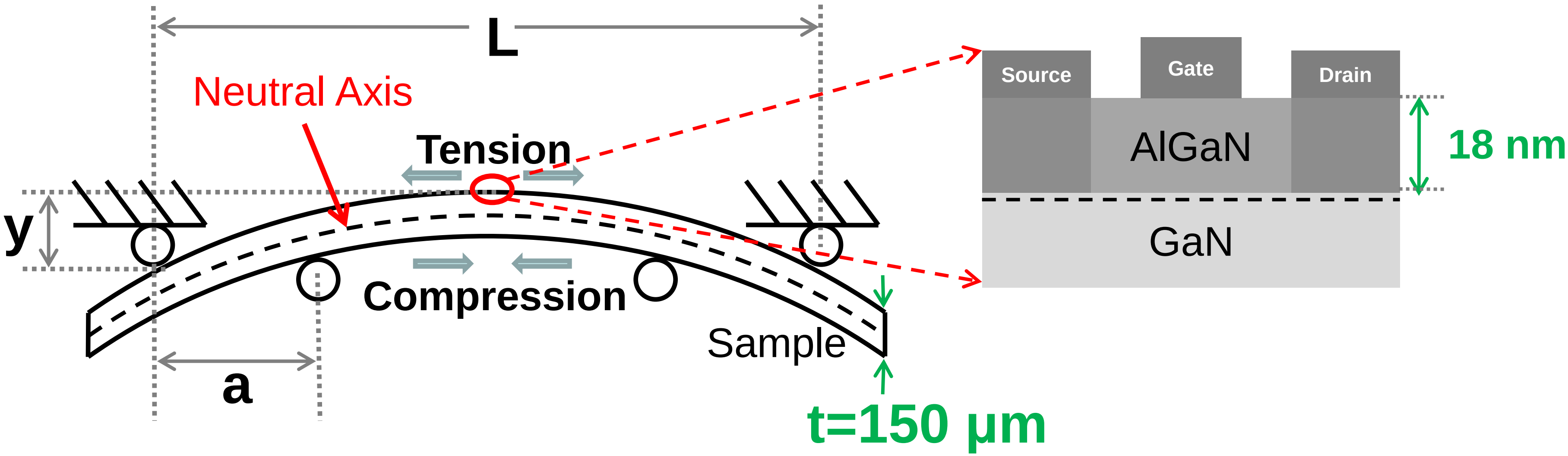
$$\rho \propto \frac{1}{n_s \mu}$$

Stress can affect GaN HEMT channel resistance through:

- 2DEG density caused by polarization
- Electron mobility

Wafer Bending (4-Point Bending)

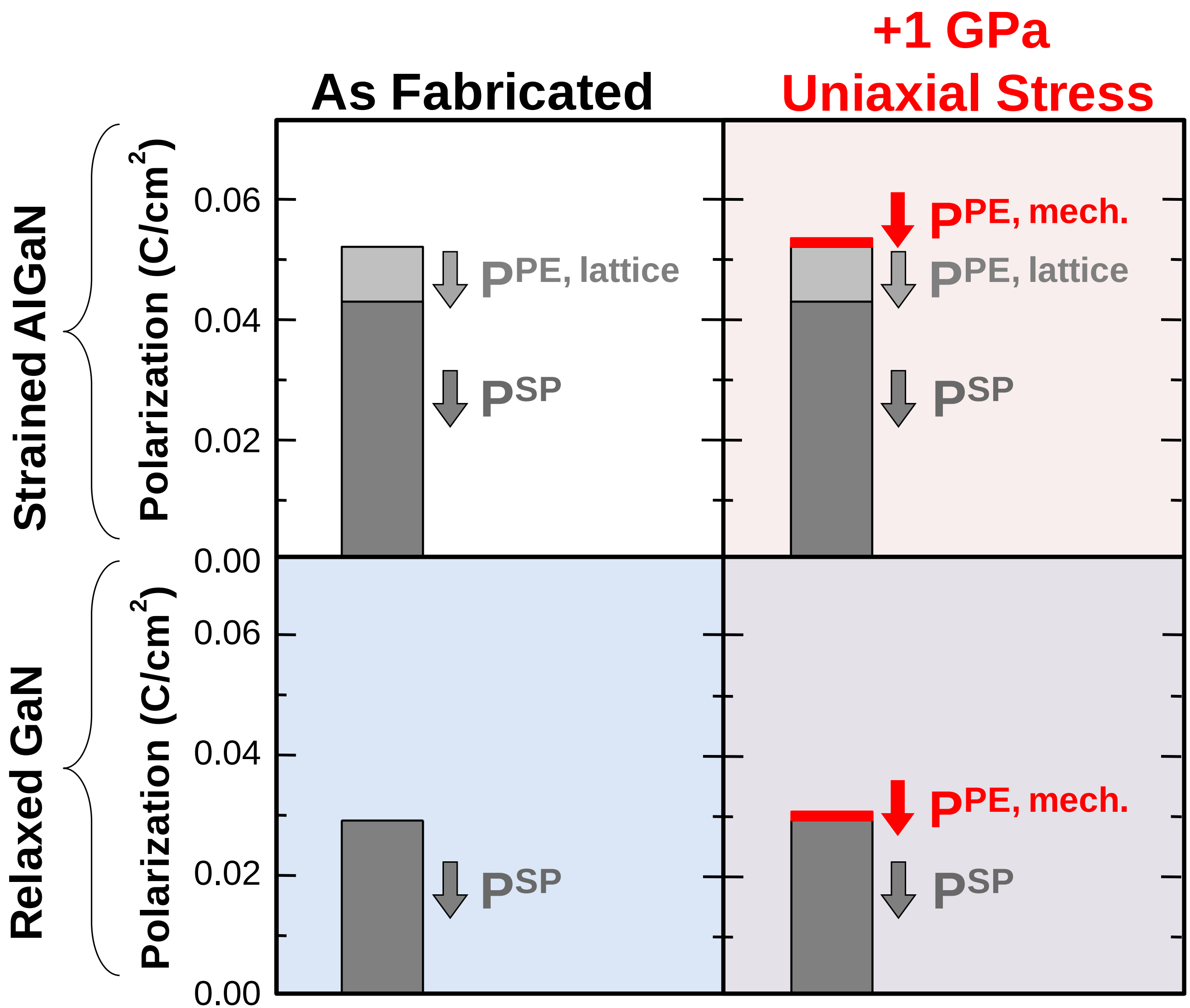
Stress on upper surface at the center of the substrate:



$$\sigma = \frac{E \cdot t \cdot y_{x=a}}{2a\left(\frac{L}{2} - \frac{2a}{3}\right)}$$

E = Young's modulus
t = sample thickness
y = vertical displacement
a, L = rod spacing

Stress Induced Polarization Change



Spontaneous Polarization (P_{SP})

- Exists if c/a ratio differs from $\sqrt{8/3}$
- Considered material parameter (independent of mechanical stress)

Piezoelectric Polarization (P_{PE})

- Electric field is generated proportional to stress (lattice mismatch or mechanical)
- Will have mechanical stress dependence

2DEG Density Calculation Procedure

AlGaN

Build in P_{SP} + $P_{PE,lattice}$

Additional strain from mechanical stress

Piezoelectric Constant

→ **$P_{PE,\ mechanical}$**

GaN

Build in P_{SP}

Additional strain from mechanical stress

Piezoelectric Constant

→ **$P_{PE,\ mechanical}$**

$$P_{total} = P_{SP}(AlGaN) + P_{PE,lattice}(AlGaN) + P_{PE,mech}(AlGaN) - P_{SP}(GaN) - P_{PE,mech}(GaN)$$

2DEG Density: $$n_s(x) = \frac{P_{total}}{e} - \left(\frac{\varepsilon_0 \varepsilon(x)}{de^2}\right)\left[e\varphi_b(x) + E_F(x) - \Delta E_C(x)\right]$$

[Ref:JAP, vol.85, pp.3222]

Simulation Uncertainty

Effective mass calculation error depends on:

- Piezoelectric coefficients
- Stiffness constants
- Tight-binding model and parameters (not considered)

  sp^3d^5 is a very accurate model (Ref. JJAP, vol.34, pp.5912)

GaN piezoelectric coefficients

e_{13}	e_{33}	e_{15}	Ref.
-0.34	-0.34	0.67	Phys. Rev. B vol.64, pp.45208
-0.22	-0.22	0.44	J. Appl. Phys. Vol.81, pp.6332
-0.33	-0.33	0.65	J. Appl. Phys. Vol.81, pp.6332

AlN piezoelectric coefficients

e_{13}	e_{33}	e_{15}	Ref.
-0.48	-0.58	1.55	IEEE Trans. Sonics Ultrason. SU-32.634

Simulation Uncertainty

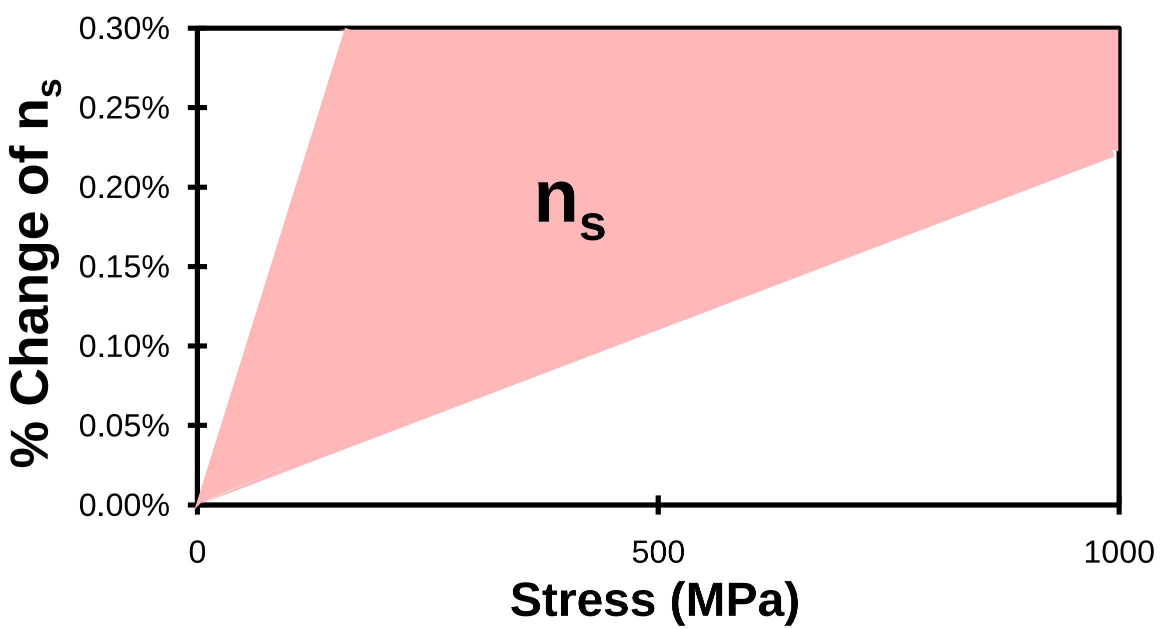
GaN stiffness constants

C_{11}	C_{12}	C_{13}	C_{33}	C_{44}	C_{66}	Ref.
37.3	14.1	8.0	38.7	9.4	11.8	J. Appl. Phys. 85,8502
39.0	14.5	10.6	39.8	10.5	12.3	J. Appl. Phys. 79,3343
36.5	13.5	11.4	38.1	10.9	11.5	J. Phys. Condens. Matter 9,24 1
37.3	14.1	8.0	38.7	9.4	11.8	J. Appl. Phys. 85,8502
37.0	14.5	10.6	39.8	10.5	12.3	Appl. Phys. Lett. 72,2400

AlN stiffness constants

C_{11}	C_{12}	C_{13}	C_{33}	C_{44}	C_{66}	Ref.
41	14	10	39	12	11.8	Appl. Phys. Lett. 72,2400
34.5	12.5	12.0	39.5	11.8	8.3	*EEE Trans. Sonics Ultrason.* SU-32,634
41.05	14.85	9.89	38.85	12.46	12.3	J. Am. Ceram. SOC. 76, 1132

Strain-Varied 2DEG Density



$$n_s(x) = \frac{+P^{int}(x)}{e} - \left(\frac{\varepsilon_0 \varepsilon(x)}{de^2}\right)\left[e\phi_b(x) + E_F(x) - \Delta E_C(x)\right]$$

Assumed independent of stress:

- ϕ_b since ΔP^{int} is small
- ΔE_C since only 26% Al in AlGaN
- ε and E_F since no change in Si and no papers reporting change for GaN

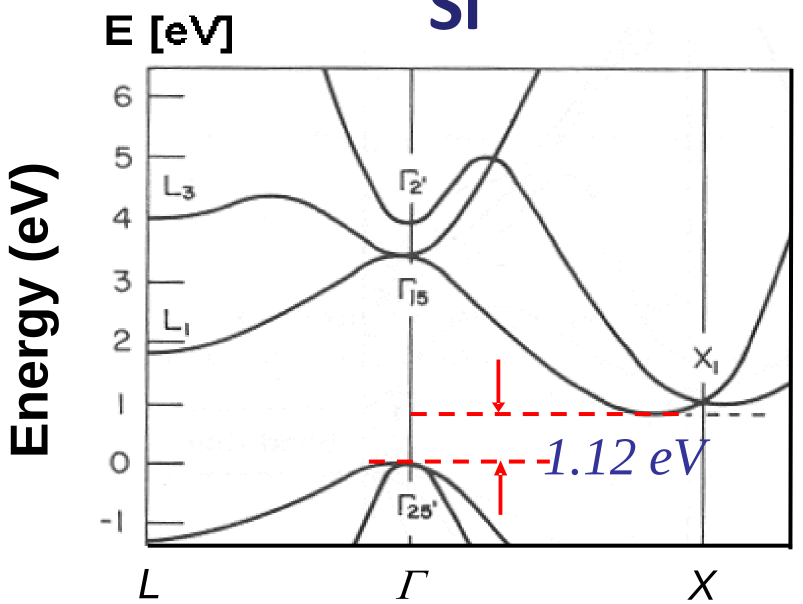
- Small changes observed in n_s (0.28%/GPa) since external stress creates offsetting piezoelectric polarizations

Mobility Relevant Factors

- Mobility
  - Effective mass
    - Carrier repopulation
    - Band warping
  - Scattering rate
    - Sub-band splitting
    - Change of DOS

Band Structure: GaN vs. Si

Si

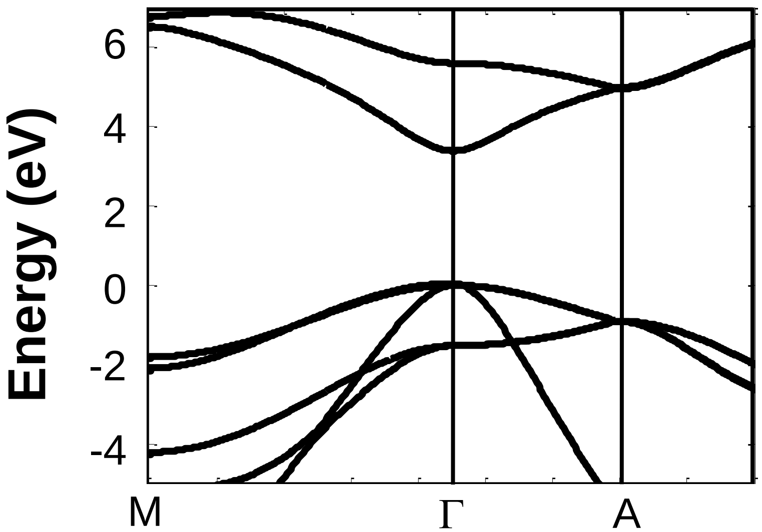


- Indirect bandgap with band minima located at the X-point
- Six equivalent conduction valleys

Mobility relevant parameters:

- Effective mass change caused by electron repopulation
- Scattering rate variation

Wurtzite GaN

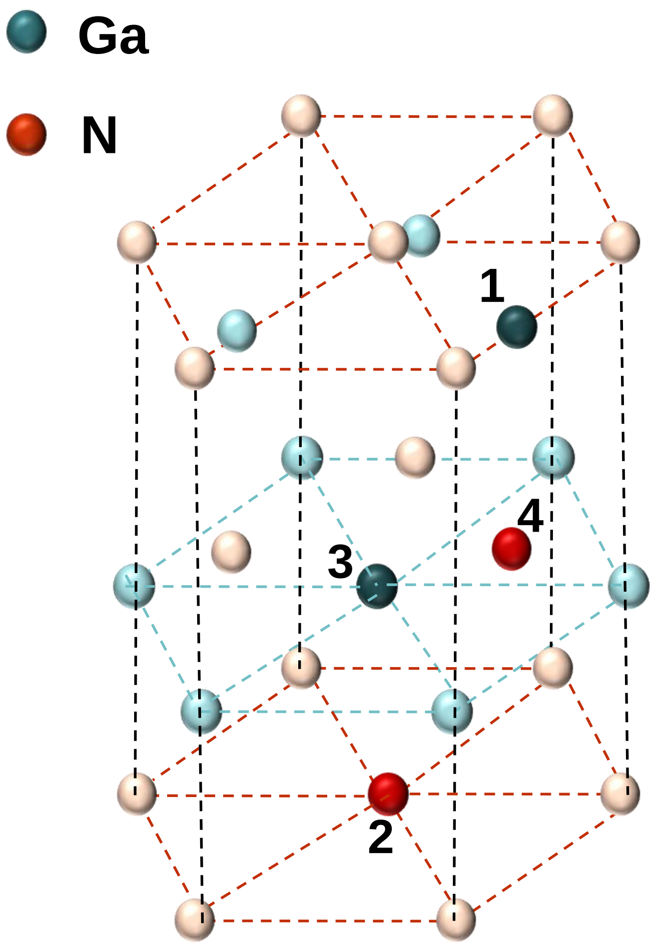


- Direct bandgap with band minimum locates at the Γ-point
- Only one conduction valley

Mobility relevant parameters:

- Effective mass change caused by conduction band warping

Tight-binding Model



$$H = \begin{array}{c} |1\rangle \\ |2\rangle \\ |3\rangle \\ |4\rangle \end{array} \overset{\begin{array}{cccc} |1\rangle & |2\rangle & |3\rangle & |4\rangle \end{array}}{\begin{bmatrix} H_{11} & H_{12} & H_{13} & H_{14} \\ H'_{12} & H_{22} & H_{23} & H_{24} \\ H'_{13} & H'_{23} & H_{33} & H_{34} \\ H'_{14} & H'_{24} & H'_{34} & H_{44} \end{bmatrix}}$$

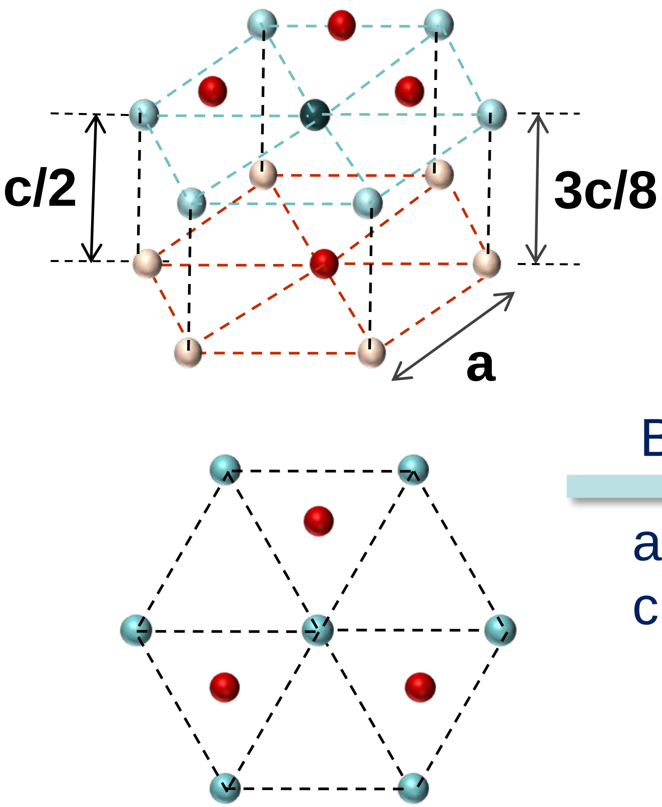
sp^3d^5 model:

- s and p orbital for N atom (total 4 orbitals)
- s, p and d orbital for Ga atom (total 9 orbitals)

Resulting 26×26 H matrix

[Ref. JJAP, vol.34, pp.5912]

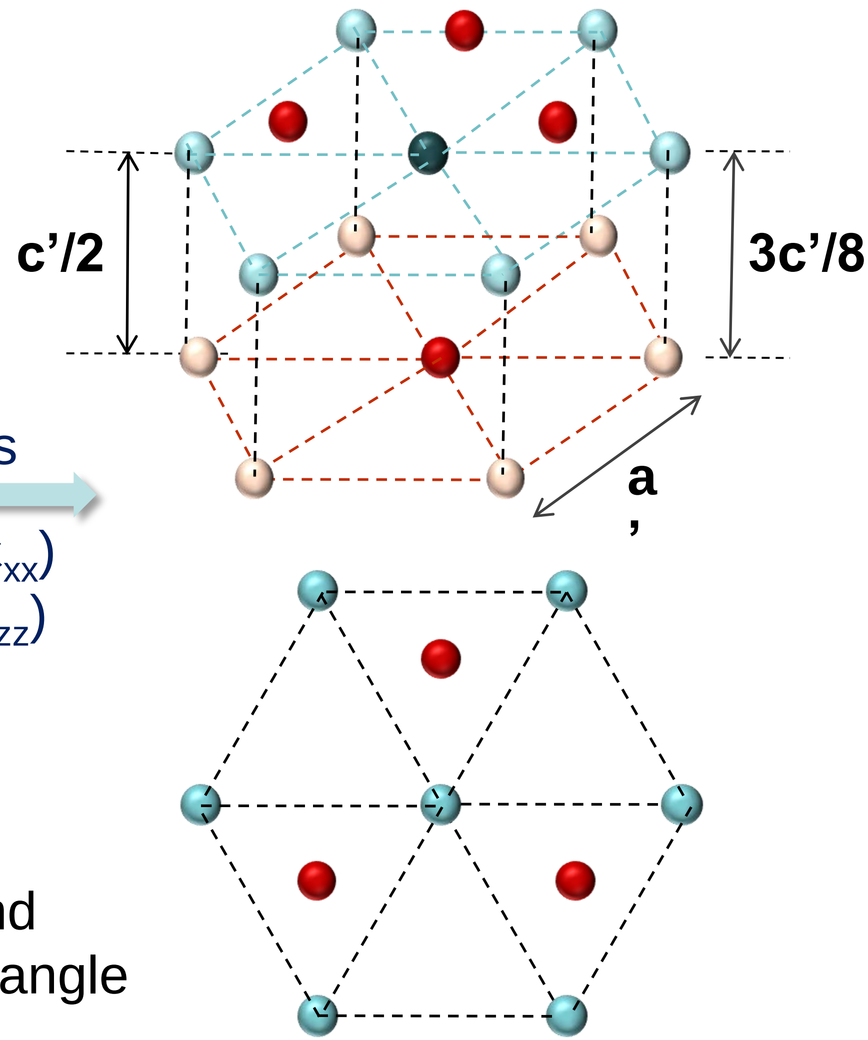
Under Biaxial Stress



Biaxial Stress

a → $a' = a(1+\varepsilon_{xx})$

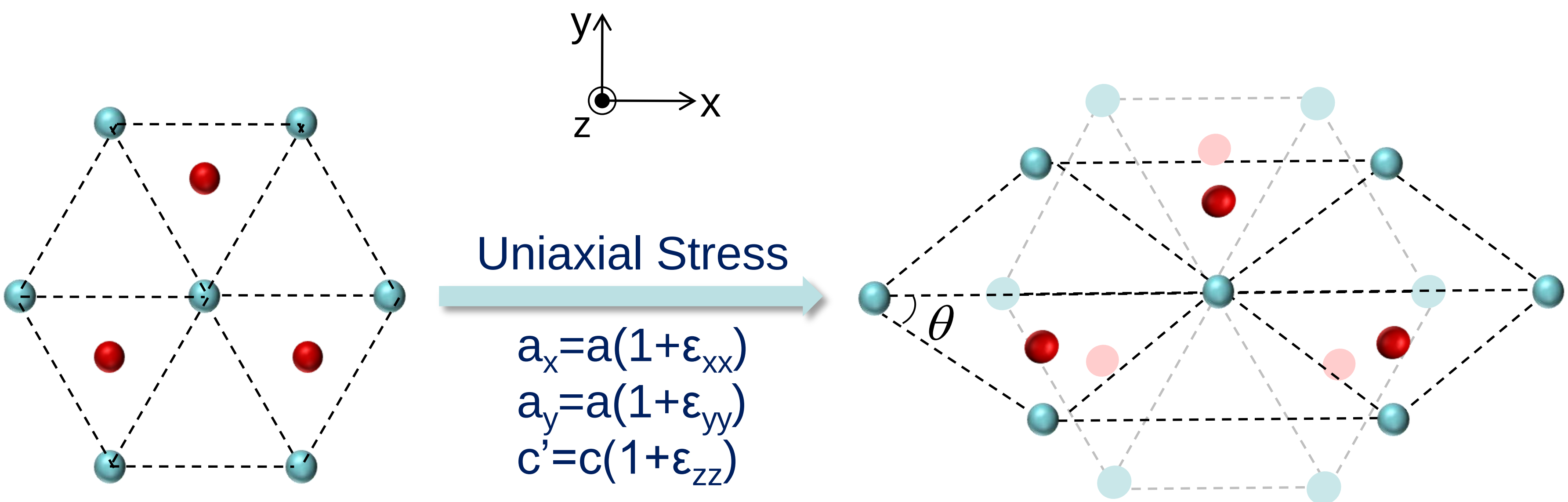
c → $c' = c(1+\varepsilon_{zz})$



- Hexagonal shape retained, only bond length changes, no change in bond angle
- Reciprocal lattice remains the same

[Ref. Phys. Rev., vol.57, pp.2382]

Under Uniaxial Stress



- Both bond length and bond angle change
- Reciprocal lattice also changes

First theoretical study on the effect of uniaxial stress on GaN HEMT

Tight-binding Parameters

E(s,N)	-12.675
E(p,N)	1.519
E(s,Ga)	-2.090
E(p,Ga)	7.838
E(d,Ga)	-19.550

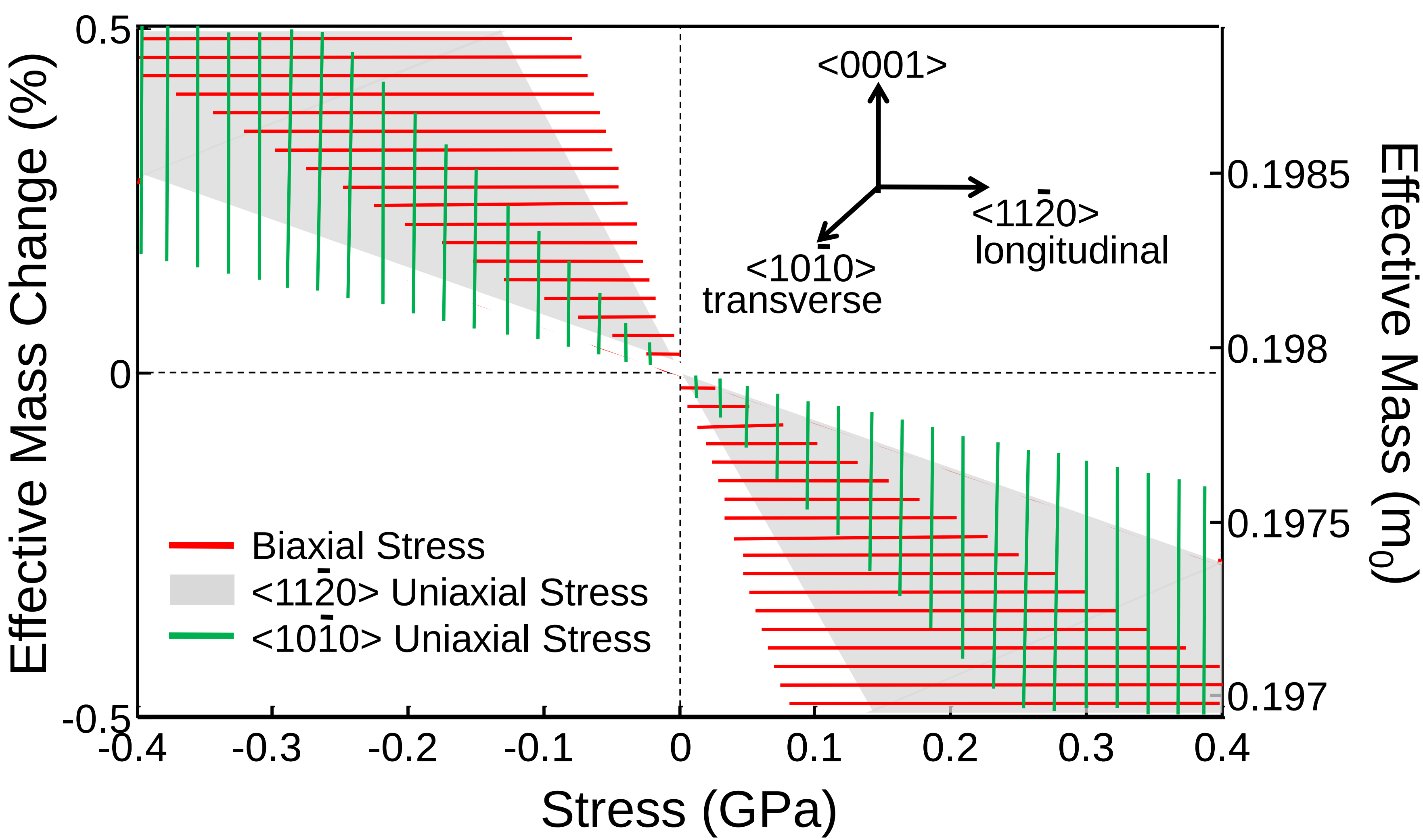
$\eta^{(1)}_{ss\sigma}$	-1.218
$\eta^{(1)}_{sap\sigma}$	-1.977
$\eta^{(1)}_{scp\sigma}$	1.626
$\eta^{(1)}_{pp\sigma}$	2.472
$\eta^{(1)}_{pp\pi}$	-0.648
$\eta^{(1)}_{sad\sigma}$	-0.400
$\eta^{(1)}_{pad\sigma}$	0.278
$\eta^{(1)}_{pad\pi}$	0.298

$\eta^{(2)}_{sas\sigma}$	0000
$\eta^{(2)}_{sap\sigma}$	0.011
$\eta^{(2)}_{pap\sigma}$	-0.110
$\eta^{(2)}_{pap\pi}$	0.000
$\eta^{(2)}_{scs\sigma}$	-0.100
$\eta^{(1)}_{scp\sigma}$	0.718
$\eta^{(2)}_{pcp\sigma}$	0.332
$\eta^{(2)}_{pcp\pi}$	-0.330

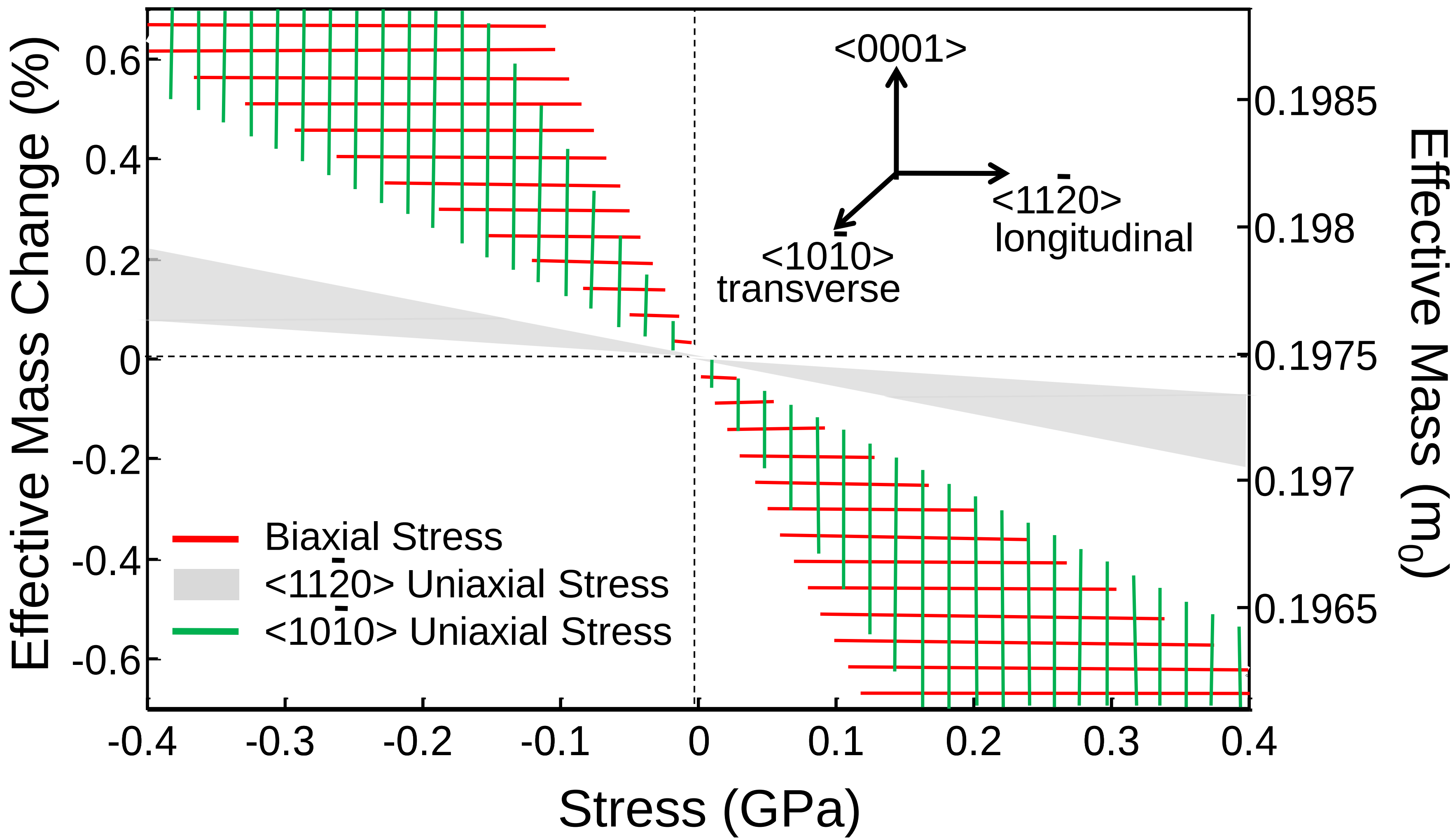
Tight-binding parameters. Onsite matrix E (eV) and coefficients $\eta = md^2V/\hbar^2$

[Ref. JJAP, vol.34, pp.5912]

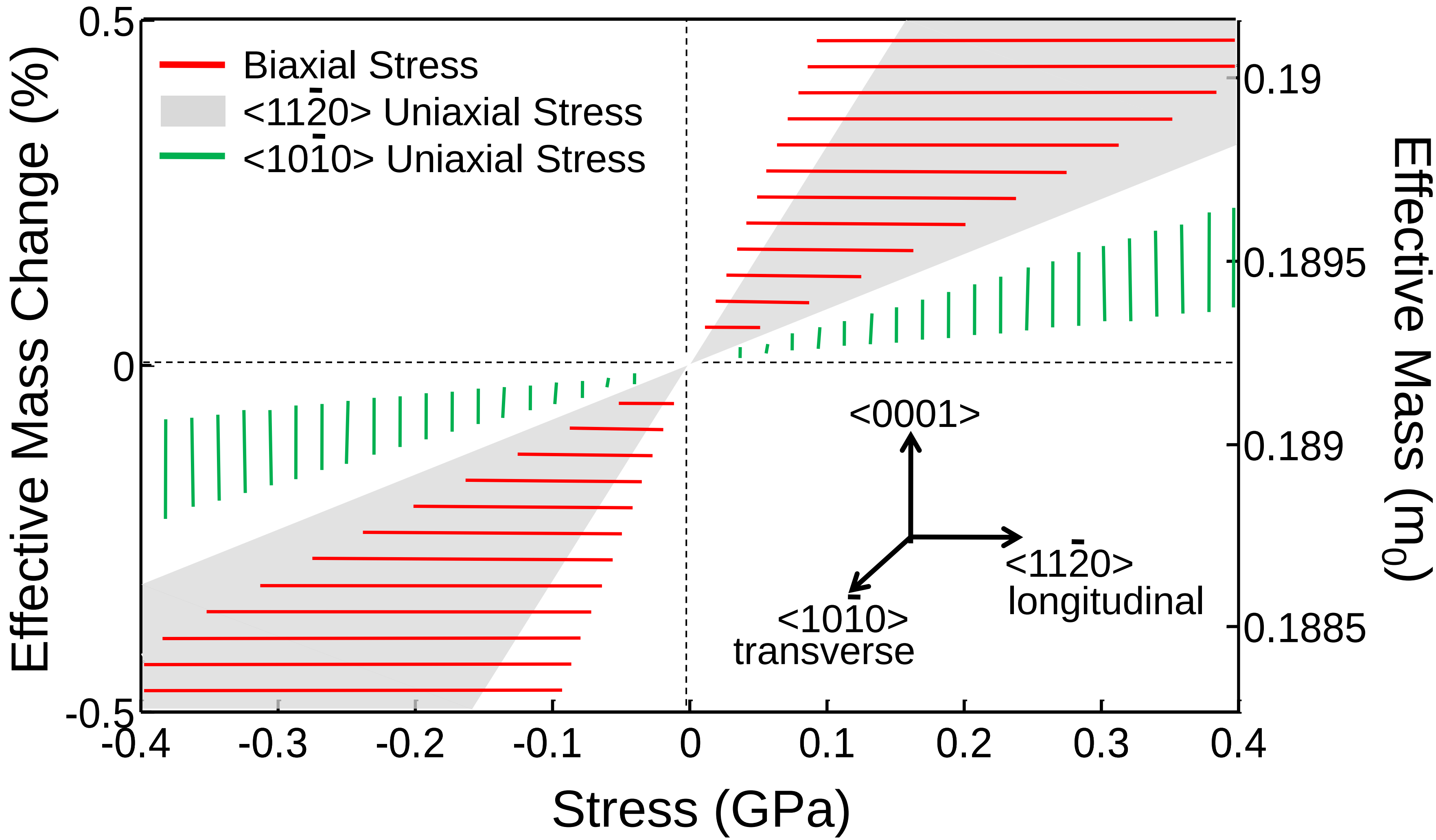
Longitudinal Effective Mass Change



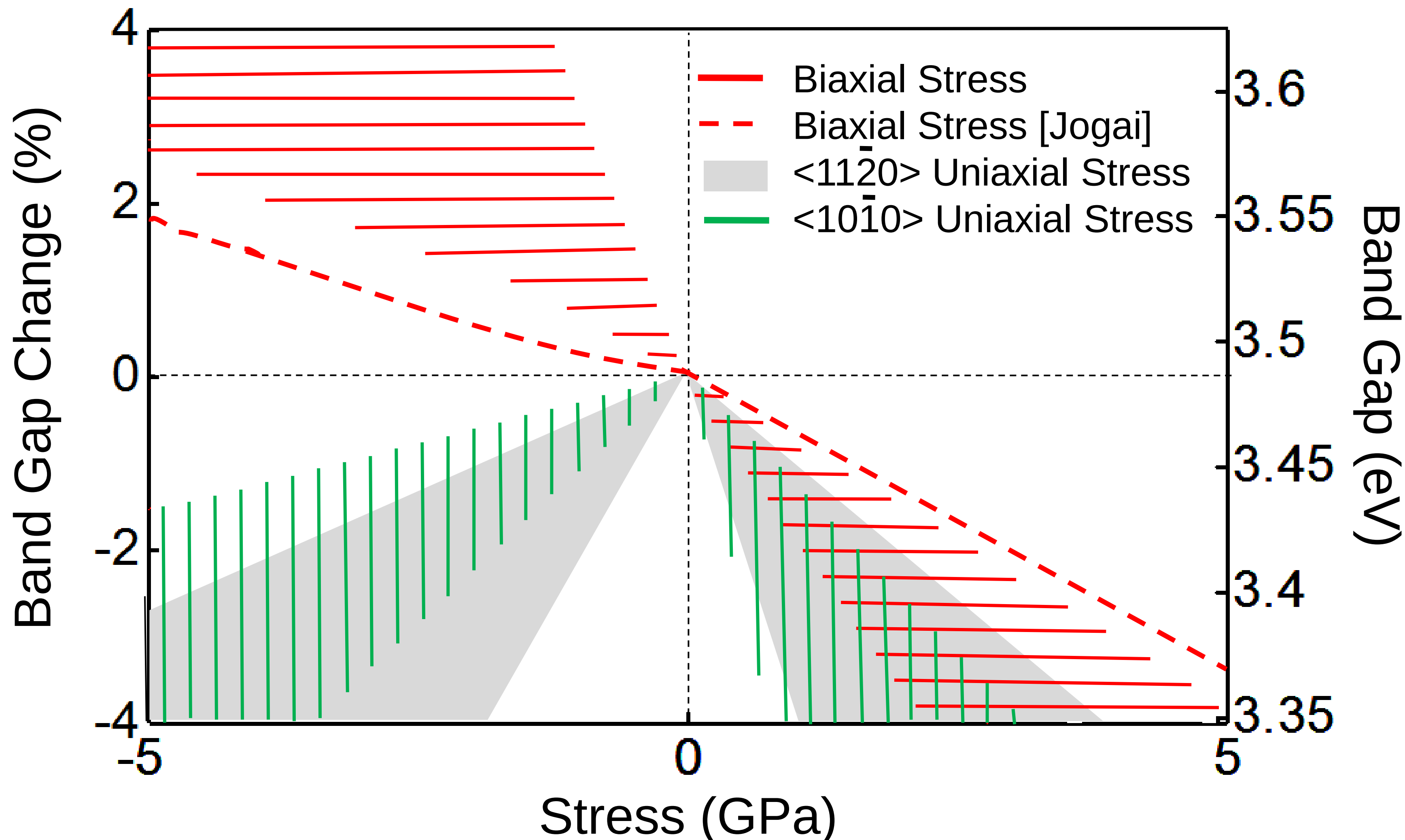
Transverse Effective Mass Change



Out-of-Plane Effective Mass Change



GaN Band Gap Change

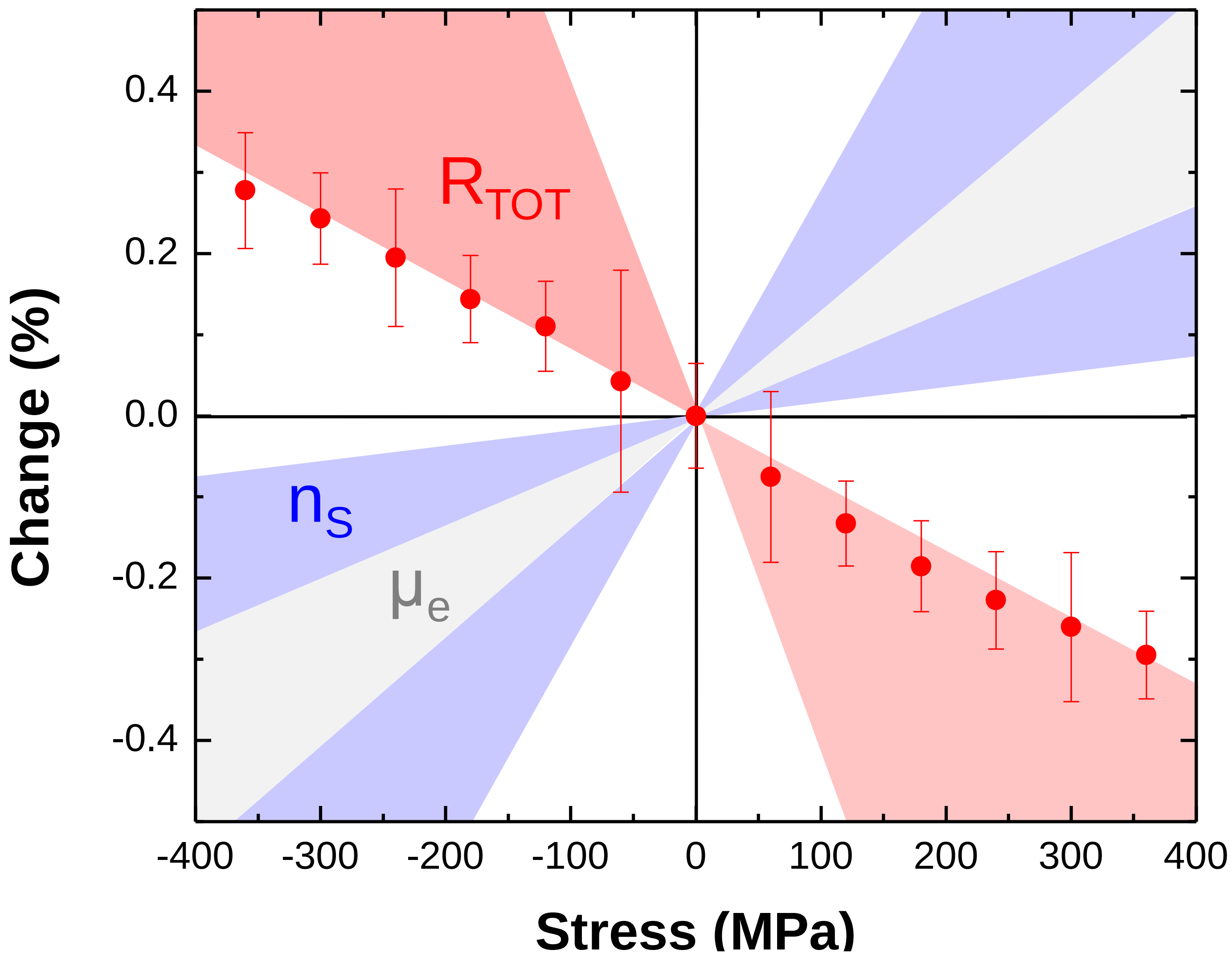


[Ref. Phys. Rev., vol.57, pp.2382]

Outline

- Motivation and review from last meeting
- Charge trapping effects
- Piezoresistance measurements
- Simulation of strain effects on 2DEG resistivity
- **Summary**
- Future plans and goals

Simulation vs. Experiment



Best Fit Parameters

Stiffness Constants

	C_{11}	C_{12}	C_{13}	C_{33}	C_{44}	C_{66}	Ref.
GaN	37.3	14.1	8.0	38.7	9.4	11.8	J. Appl. Phys. 85,8502
AlN	41	14	10	39	12	11.8	Appl. Phys. Lett. 72,2400

Piezoelectric Coefficients

	e_{13}	e_{33}	e_{15}	Ref.
GaN	-0.22	-0.22	0.44	J. Appl. Phys. Vol.81, pp.6332
AlN	-0.48	-0.58	1.55	IEEE Trans. Sonics Ultrason. SU-32.634

Feed-forward into reliability simulator

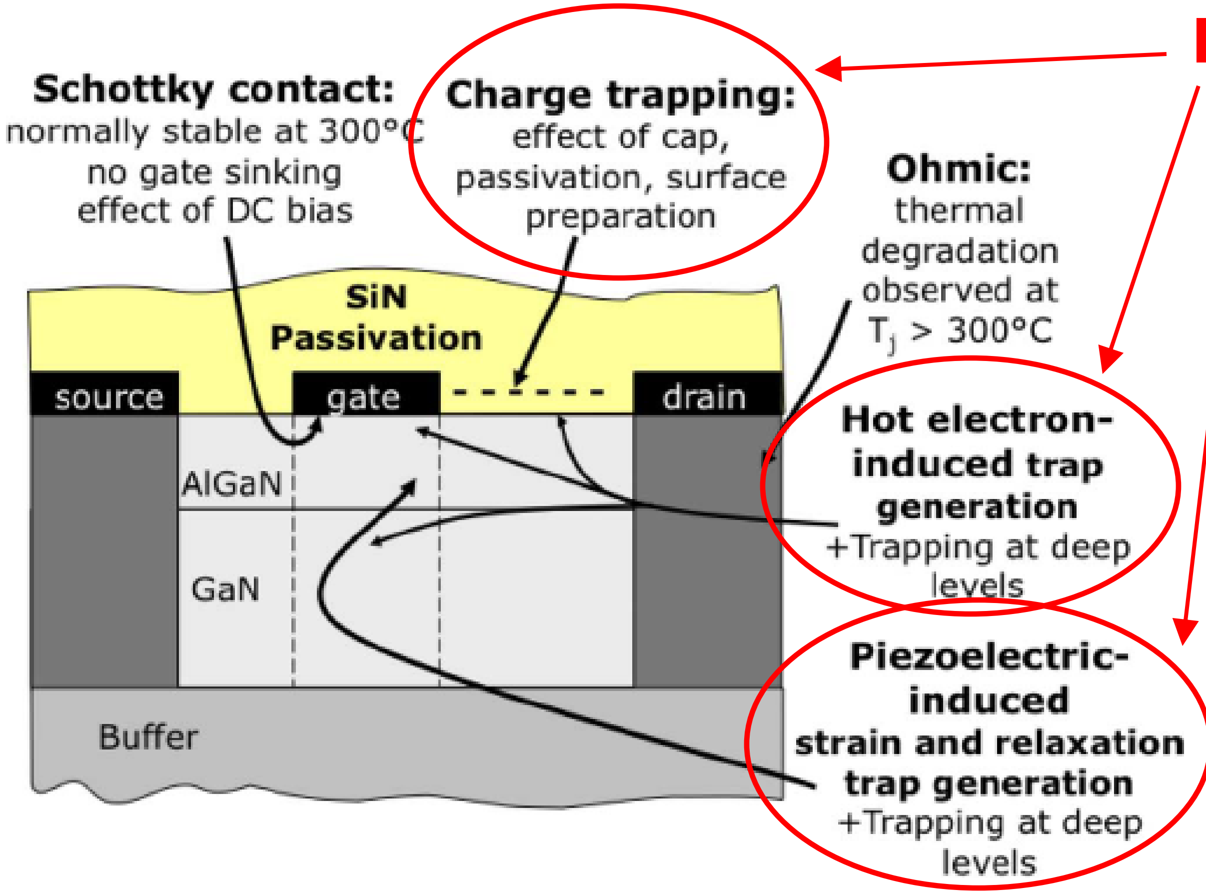
Outline

- Motivation and review from last meeting
- Piezoresistance measurements
- Simulation of strain effects on 2DEG resistivity
- Summary
- **Future plans and goals**

Future plans and goals

- Continue investigation of GaN HEMT failure mechanisms influenced by stress
- Focus includes stress dependence of gate current
  - Trap energy level
  - Schottky barrier height
  - Out-of-plane effective mass
- Calibrate simulations to select 'best-fit' parameters
- Feed-forward into reliability simulator

Failure Mechanisms in GaN HEMTs



Influenced by stress

- carrier mobility
- polarization and 2DEG
- trap energy levels
- Schottky barrier height
- bandgap
- generation of traps

G. Meneghesso, et al., IEEE Trans on Device and Materials Reliability, Vol. 8, 2, 2008

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  - Robert Dieme
  - Ukjin Roh